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RADIO STARS AND THEIR LIVES IN THE GALAXY

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ABSTRACT

This paper summarizes the three-day international workshop *Radio Stars and Their Lives in the Galaxy*, held at the Massachusetts Institute of Technology Haystack Observatory on 2012 October 3-5. The workshop was organized to provide a forum for the presentation and discussion of advances in stellar and solar astrophysics recently (or soon to be) enabled by the latest generation of state-of-the-art observational facilities operating from meter to submillimeter wavelengths. The meeting brought together both observers and theorists to discuss how radio wavelength observations are providing new and unique insights into the workings of stars and their role in the Galactic ecosystem. Topics covered included radio emission from hot and cool stars (from the pre- to post-main-sequence), the Sun as a radio star, circumstellar chemistry, planetary nebulae, white dwarf binaries and novae, supernova progenitors, and radio stars as probes of the Galaxy.

Subject headings: meeting summary, Stars — stars: AGB and post-AGB – stars: winds, outflows – circumstellar matter – radio lines: stars

1. BACKGROUND AND MOTIVATION FOR THE WORKSHOP

Radio emission has now been detected from stars across the entire Hertzsprung-Russell (H-R) diagram, spanning virtually every stage of stellar evolution. The recent commissioning of a host of new and upgraded observational facilities operating at wavelengths spanning from the meter to the submillimeter has been leading to a rapid pace of discoveries in nearly every branch of stellar astrophysics. Motivated by these advances, a 3-day workshop entitled "Radio Stars and Their Lives in the Galaxy" was convened at the Massachusetts Institute of Technology (MIT) Haystack Observatory in Westford, Massachusetts on 2012 October 3-5. The workshop drew a total of 50 participants from four continents and 13 countries and brought together both theorists and observers to participate in a program of oral presentations, posters, and discussions. The scientific program was devised to bring together stellar astrophysicists from a variety of sub-disciplines to stimulate cross-fertilization of ideas on unsolved problems common to the study of many classes of stellar objects (e.g., mass loss, the driving of bipolar outflows, and the generation of magnetic fields).

The first international workshop on Radio Stars took place in Ottawa, Canada in June 1979, at which time the discipline of stellar radio astronomy was approximately a decade old (Feldman & Kwok 1979). The Very Large Array (VLA) had not yet been commissioned, hence available data were largely limited to single-dish flux density measurements at centimetric wavelengths without the advantages of imaging. Thirty-three years later, the Haystack workshop made abundantly clear that stellar radio astronomy remains a vibrant field that is witnessing a rapid pace of advances relevant to many of the most important topics in stellar astrophysics. We witnessed how new technologies are bringing dramatic advances in areas such as resolved imaging of radio photospheres, molecular line imaging, dynamic imaging spectroscopy, high-precision astrometry, and the routine study of sources at a level of a few tens of μJy. We also heard how developments in theory, modeling, and laboratory astrophysics are improving our ability to interpret results. This paper attempts to summarize a sampling of the diverse array topics presented and discussed at the Haystack workshop.

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2. SCIENTIFIC SESSIONS

The science program of the Haystack Radio Stars workshop comprised 33 oral presentations (13 invited reviews and 20 contributed talks) and 7 posters. The complete program and presentation abstracts are available at http://www.haystack.mit.edu/workshop/Radio-Stars/.

The workshop was organized into seven scientific sessions: (I) An Overview of Stellar Radio Astronomy; (II) Radio Emission from Pre-Main Sequence Stars; (III) Radio Emission on the Main Sequence; (IV) Post-Main Sequence Radio Stars; (V) Stellar Remnants; (VI) Radio Stars as Players in our Galaxy; (VII) Summary and Perspectives. This summary paper loosely follows this organization, but also attempts to synthesize recurrent themes and topics that spanned multiple sessions. In addition to summarizing new results presented by participants, I strive to draw attention to topics where there was a consensus that our understanding is still limited, where controversies persist, and/or where future investigations are likely to prove fruitful. I close with a summary of concerns and future challenges raised during the final discussion session.

3. AN OVERVIEW OF STELLAR RADIO ASTRONOMY

M. Güdel (University of Vienna) opened the workshop with a comprehensive overview of the versatility of the radio spectrum for understanding physical processes in stars across the entire H-R diagram. He reviewed radio emission mechanisms important for stellar sources and emphasized that magnetic fields have now been shown to be important in nearly every type of stellar radio source. This point was underscored in many subsequent talks. Güdel cited several "keywords" expected to define the future of stellar radio astronomy, including *μJy sensitivity*, *time resolution, bandwidth, spectral resolution*, and *frequency coverage*. S. Kwok (The University of Hong Kong) reminded us of another during his closing talk: *dynamic range*. Thanks to the truly impressive suite of new and upgraded radio facilities that has come online during the past few years, the workshop provided no shortage of illustrations of how recent gains in each of these key areas are leading to breakthroughs in our understanding of the workings of stars.

4. RADIO EMISSION FROM PRE-MAIN SEQUENCE STARS

4.1. *The Radio-X-ray Connection in Young Stellar Objects*

It has been known for some time that young stellar objects (YSOs) are producers of both X-ray and centimetric radio emission. However, as summarized by S. Wolk (Harvard-Smithsonian Center for Astrophysics), to date X-ray and radio observations of young clusters have revealed a paltry number of simultaneous detections, with only a few percent of YSOs found to show both types of emission (Forbrich et al. 2011; Forbrich & Wolk 2013). This comes as a surprise, since many of the YSOs are predicted to be bright enough for detection in the radio based on the Güdel-Benz relation[2], yet fall short by two orders of magnitude or more. At the same time, several of the YSOs that are detected in the radio lie *above* the Güdel-Benz relation. Further, the radio detections are not correlated with any identifiable X-ray properties of the sources. Together these results suggest that in YSOs the X-ray and radio emission are decoupled.

As described by Wolk, the Jansky Very Large Array (JVLA) is soon expected to dramatically extend progress in YSO studies, providing a jump by a factor of ∼20 in sensitivity over past VLA studies. This will greatly improve radio detection statistics and allow polarization measurements for many more sources. In addition, the JVLA will provide the spectral coverage critical for obtaining radio spectral indices and thus distinguishing between thermal and non-thermal emission mechanisms. Wolk described an ongoing campaign to simultaneously observe regions of Orion with *Chandra* and the JVLA, with first results expected in late 2012.

4.2. *Radio Emission from the Jets of Young Stellar Objects*

In addition to their disks, winds, and coronae, the jets from YSOs are also a source of centimetric radio emission. Dust-penetrating radio observations of these jets provide the best available tool for addressing the still poorly understood problem of their launch and collimation. R. Ainsworth (Dublin Institute for Advanced Studies) presented a 16 GHz continuum study of a sample of 16 Class 0 and Class I YSOs using the Arcminute Microkelvin Imager. Spectral indices derived from a combination of the new measurements and other radio/submm measurements from the literature point to thermal bremsstrahlung as the dominant jet emission mechanism. This work also established that dust emissivity is important even at centimeter wavelengths and that uncertainties in the dust opacity index comprise the dominant uncertainty in calculations of the luminosity of YSOs from radio data (Ainsworth et al. 2012).

[2] The Güdel-Benz relation (Güdel & Benz 1993; Benz & Güdel 1994) is a tight empirical correlation between the quiescent X-ray luminosity and radio luminosity for active stars that spans more than 10 orders of magnitude. This relationship suggests an intimate connection between the non-thermal electrons responsible for the radio emission and the thermal plasma giving rise to the X-rays.

5. RADIO EMISSION FROM COOL MAIN SEQUENCE STARS

5.1. *Emission from Ultracool Dwarfs*

The interiors of stars later than ∼M3 are thought to be fully convective, predicting a breakdown in the $\alpha\Omega$ dynamo mechanism for generating stellar magnetic fields. Furthermore, at the ultracool end of the H-R diagram ($\gtrsim$M7), X-ray and Hα emission are seen to dramatically decline relative to the stellar bolometric luminosity, indicating sharp drops in chromospheric and coronal heating. Consequently, perhaps one of the greatest surprises in stellar radio astronomy in the past decade has been the discovery of radio emission from ultracool (late M, L, and T) dwarfs well in excess of what is predicted from the Güdel-Benz relation, together with indications of very strong magnetic fields in some cases.

As described in the review by G. Hallinan (California Institute of Technology), the emission from ultracool dwarfs has been found to comprise both broadband, quiescent emission and periodic pulse-like flares. These flares are nearly 100% circularly polarized and are rotationally modulated, analogous to beamed radiation from pulsars. This points to an electron cyclotron maser as the most likely emission mechanism—the same mechanism responsible for the radio emission from the planets in our solar system (e.g., Hallinan et al. 2007, 2008; Figure 1). Importantly, this means that the observed frequency cutoff of the emission can be directly translated into a measure of the magnetic field strength, with values in the kilogauss range reported for the late M dwarfs and brown dwarfs studied to date.

Rotation increases rapidly from the late M through the T dwarfs, and the correlation between radio luminosity and rotation rate was noted by several speakers. M. Güdel drew attention to a recent survey of ∼100 late-M and L dwarfs by McLean et al. (2012) that found that for spectral types $\gtrsim$M7, the ratio of radio to bolometric luminosity increases with rotational velocity without saturating. This result underscores that rotation controls the magnetic activity and the production of the high energy electrons responsible for the radio emission in these cool stars. However, it is not yet clear whether rotation is powering the activity or the electron acceleration. Güdel suggested that a possible explanation for why saturation does not occur at radio wavelengths is that there are changes in surface effects and or filling factors in the latest types stars. For example, magnetic field configurations that trap electrons and keep them levitated off the surface of the star would force them to lose their energy via synchrotron emission rather than colliding with other particles and thermalizing. At the same time, low densities would explain why there is not much X-ray emission. On a related note, S. Cranmer (Harvard-Smithsonian Center for Astrophysics) suggested that the combination of X-ray and radio observations might help to establish whether there is truly a basal "floor" to the

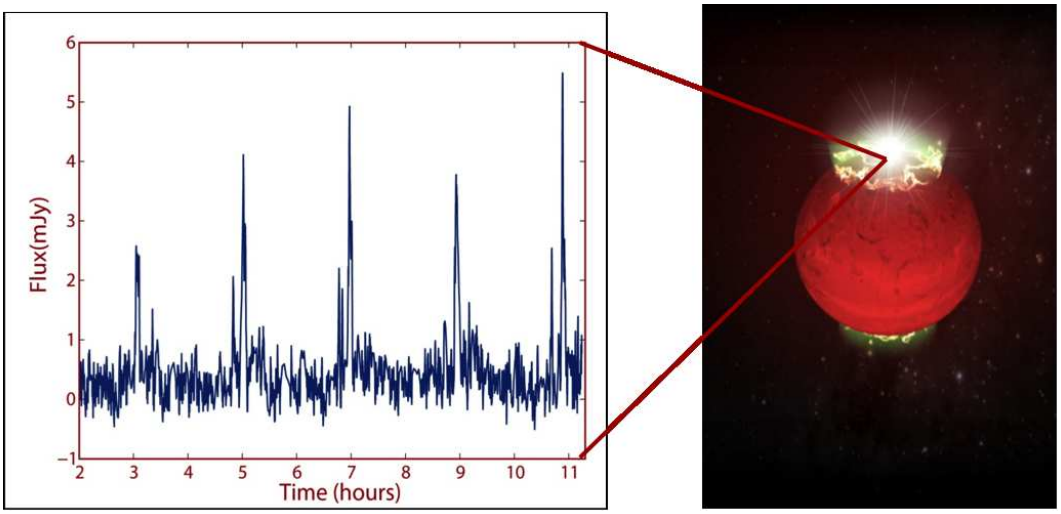

FIG. 1.— *Left:* An 8.44 GHz VLA light curve of the total intensity (Stokes I) emission from the M9 dwarf TVLM 513-46546 (Hallinan et al. 2007). Periodic bursts of coherent emission are evident. *Right:* Artist's conception of the radio-emitting region from an ultracool dwarf (courtesy of G. Hallinan).

age-rotation-activity relationship.

Hallinan and Güdel both highlighted the significance of the recent detection of 4.75 GHz radio emission from a T6.5 dwarf by Route & Wolszczan (2012) using Arecibo. At $T_{\rm eff} \approx 900$ K, this star is $\sim$1000 K cooler than any other dwarf detected in the radio to date. Its derived field strength of $\sim$1.7 kG poses severe challenges for existing dynamo theories for magnetic field generation. Radio measurements offer the only means of quantifying magnetic field strength in this regime between stars and planets, since other traditional techniques (e.g., exploiting the Zeeman effect) break down as molecular lines become too rotationally broadened to yield useful measurements.

Despite the weakness of the optical and Hα emission from ultracool dwarfs, Hallinan noted that in all cases where pulsed emission has been detected, periodic variability in the broadband optical light and Hα emission is also seen. He proposed that the periodic emission across the entire spectrum from optical to radio is auroral in nature. As a test of this idea, Hallinan cited results from a new program aimed at obtaining simultaneous JVLA dynamic spectra and Keck optical spectrophotometry. The JVLA dynamic spectra of three sources observed to date permit derivation of the magnetic field strength as a function of height, effectively mapping the auroral oval of the sources. Correlated, periodic variability is also present across the optical spectrum, arising from photospheric and chromospheric hot spots. The nature of the activity revealed in these objects can be understood as being produced from large-scale, quasi-stable currents in the magnetic fields rather than as a result of traditional coronal activity. Comparison of these data with new models (e.g., Kuznetsov et al. 2012) is expected to permit discrimination between satellite-induced emissions versus rotationally modulated emissions.

In spite of rapid growth in the study of ultracool dwarfs at radio wavelengths, Güdel and Hallinan both cautioned that only a minority of cool dwarfs have so far been detected in the radio, and larger surveys of cooler stars are needed for improving statistics and for gaining insight into the question of why only a fraction of brown dwarfs are active. Another open question is how the electrons are accelerated in ultracool dwarfs. Hallinan predicted that lessons from planetary magnetospheric physics may hold answers. Finally, the nature of the *quiescent* emission from ultracool dwarfs (which shows some modest variability) is still poorly understood. Gyrosynchrotron emission is one candidate. Its relation to the pulsed emission is also unknown.

5.2. *Radio Detection of Exoplanets?*

While no exoplanets have been detected in radio emission to date, recent results from the study of ultracool dwarfs bode well for future success in this area. Hallinan suggested hot Jupiters as the most promising candidates (e.g., Hallinan et al. 2013), and that searches at frequencies of a few 10s of MHz are likely to be the most fruitful. These bands will be accessible with new facilities including the Long Wavelength Array (LWA), the Low-Frequency Array for Radio Astronomy (LOFAR), and the Murchison Widefield Array (MWA). Related studies will also be possible using a new low-frequency array under construction in Owens Valley (with Hallinan as Principal Investigator) that will image the entire sky every second and reach sensitivities of $\sim$10 mJy hourly. Completion is expected in March 2013.

5.3. *Radio Emission from Flare Stars*

Historically, bandwidth limitations have largely precluded the study of coherent bursts/ plasma emission on stars other than the Sun. However, this is rapidly changing, and some spectacular new examples of stellar dynamic spectroscopy were presented at the meeting. T. Bastian (National Radio Astronomy Observatory) described Arecibo observations of a burst from the active flare star AD Leo that was found to be nearly 100% right circularly polarized and whose emission mechanism appears to be the cyclotron maser instability. The resulting dynamic spectrum showed a spectacular range of structure, including fast-drift striae that appear to be analogous to the auroral kilometric radiation in the terrestrial magnetosphere (Osten & Bastian 2008).

G. Hallinan reported JVLA observations of the canonical flare star UV Ceti (a binary comprising two M5.5 dwarfs, each with a mass of $\sim 0.1 M_{\odot}$), spanning the entire spectral range from 1-40 GHz. Both components of the binary were detected in all bands, and one surprise is that the emission is brighter at higher frequencies (20-40 GHz) than at lower frequencies, possibly implying the detection of gyroresonance emission from the thermal corona. A second intriguing finding was the serendipitous detection of a sweeping flare during the observations. This flare was bright enough to detect on a single baseline (implying the transport of significant amounts of plasma within the corona of the star) with 100% circular polarization. The flare sweeps in the opposite direction expected for a coronal mass ejection, suggesting that it is instead a downward moving type III-like burst—the first ever detected on a star other than the Sun.

Hallinan's recent discoveries motivated the creation of the "Starburst" program at the Owens Valley Solar Array. Led by Hallinan, it will perform night time dynamic spectroscopy of active stars over 1-6 GHz on a single baseline between two 27m dishes, with simultaneous optical monitoring. Triggered follow-up with the Very Long Baseline Array (VLBA) could then be used to check for resolved gyrosynchrotron emission (i.e., effectively imaging coronal mass ejections on other stars).

R. Osten (Space Telescope Science Institute) pointed out a puzzle concerning stellar transients detected by *Swift* in hard X-rays. She noted the case of the flare star EV Lac, where the X-ray luminosity exceeded the bolometric luminosity during the flare (Osten et al. 2010), suggesting that Jy-level gyrosynchrotron flares should occur according to the Güdel-Benz relation. However, there is no clear evidence yet that the radio counterpart to these types of flares has ever been seen.

5.4. *Magnetic Chemically Peculiar Stars*

S. White (Air Force Research Laboratory) drew attention to magnetic CP stars as yet another category of stars exhibiting electron cyclotron maser emission. He cited a recent study of CU Vir by Trigilio et al. (2011) that showed evidence for beaming orthogonal to the magnetic field lines—quite different from the familiar case of Jupiter.

5.5. *The Time Domain in Cool Star Astrophysics*

The importance of the time domain in stellar radio studies was a recurrent theme in talks spanning every topic from ultracool dwarfs to evolved stars to novae and supernovae. This topic was reviewed for the case of cool, magnetically active stars by R. Osten.

One point emphasized by Osten is that stellar variability at mm wavelengths has yet to be thoroughly investigated. While mm emission from young stars is typically ascribed to dust emission from disks, some YSOs have shown spectacular mm flares that have periodicity comparable to the orbital period. These can be interpreted as synchrotron emission from interacting magnetospheres based on their spectra and timescales. Such flares provide access to the highest energy electrons from flaring stars and may impact spectral energy distribution (SED) fitting for YSOs. Osten reminded us that a decade ago, Bower et al. (2003) predicted that a single exposure of Orion with the Atacama Millimeter/Submillimeter Array (ALMA) that reaches $\sim 10\mu$Jy sensitivity would uncover hundreds if not thousands of flares. She noted that it will be particularly interesting to test this prediction in light of the relatively radio-quiet behavior of Orion stars at centimeter wavelengths described by Wolk (§4.1).

Osten also drew attention to the work of Richards et al. (2003), who found cyclic radio flaring from the active binary HR 1099 and elevated states that can persist for many times longer than the rotation period. A decade later, this phenomenon is still not understood. This is also an example of the importance of long-term monitoring campaigns with sampling on a range of timescales for uncovering new phenomena.

The Güdel-Benz relation (see above) is commonly interpreted as indicating that there is a common reservoir out of which both particle acceleration and plasma heating are occurring. Osten explored the question of what happens if one also considers the time axis of this relation. Based on data for five stars, she found that the range of variation in radio luminosity was much larger than that of X-ray luminosity over time, a fact that may be related to the finding that X-ray emission appears to be saturated for ultracool stars while radio emission does not (see also §5.1).

Also relevant to time domain studies of low-mass stars, J. Posson-Brown (Harvard-Smithsonian Center for Astrophysics) presented a poster advertising Project Tanagra, a spectro-temporal database of *Chandra* X-ray grating observations of bright low-mass coronal stars. These data have excellent spectral and timing resolution, and this database is expected to provide a useful complement to radio studies of variability in these objects.

6. THE SUN AS A RADIO STAR

S. White provided an overview of radio emission from our nearest star. He began by reviewing the four main emission mechanisms responsible for the production of solar radio emission: *bremsstrahlung* (thermal plasma; dominant in most of the corona); *gyroresonance* (arising from strong magnetic fields in the corona, and producing the optically thick emission observed from active regions); *gyrosynchrotron* (from non-thermal electrons in flares); and *plasma emission* (which produces highly polarized bursts at low frequency). Electron cyclotron maser emission (discussed extensively at the workshop in the context of ultracool stars), can be considered as a variation of gyroresonance. As one moves across the radio spectrum, solar radio emission goes from being optically thick coronal emission at frequencies below 300 MHz to optically thin emission at cm wavelengths to optically thick chromospheric emission in the mm regime.

White noted that one of the most powerful aspects of solar radio emission is its ability to see everything in the solar atmosphere that can be seen at other wavelengths—and more. In his review talk, White also "laid down the law" with regard to using the Sun as an analogy for understanding stellar radio emission, describing how solar behavior informs what we see at radio wavelengths from other stars. He also highlighted cases where this analogy breaks down, as well as some of the key outstanding problems in solar radio astronomy (see below).

6.1. *The Sun at Low Frequencies*

D. Oberoi (National Centre for Radio Astrophysics) reminded us why solar imaging is such a challenge: a large angular size and complex morphology, a large dynamic range in the brightness of features, and temporal variations on timescales ranging from milliseconds to years. Thus to effectively image the Sun at radio wavelengths, an interferometric array must simultaneously deliver high fidelity and high dynamic range imaging over a broad observing band with high time and frequency resolution. A dense sampling of the *u*-*v* plane is particularly important, since time and frequency synthesis can obscure valuable information for a dynamic source like the Sun. Both short and long spacings are also important to resolve both the solar disk and fine-scale structures, respectively. Oberoi described how such performance requirements are being met for meter wavelength science (80-300 MHz) by the MWA, which is currently nearing completion in the extremely radio quiet Western Australian Outback.

Oberoi presented several examples of early science results from MWA prototype arrays that have recently operated on site. He showed images obtained at 193 MHz from a 32-element engineering prototype array that exceed by an order of magnitude the dynamic range previously achieved at similar frequencies. These data have permitted some of the first simultaneous imaging of thermal and non-thermal coronal emission at meter wavelengths (Oberoi et al. 2011; Figure 2). Corresponding dynamic spectra also reveal a plethora of fine structures and other non-thermal features not previously detectable with existing solar spectrometers, as well as dramatic changes in the solar plasma on timescales of less than one second. These data bode well for the new insights into the solar corona expected to come from the full MWA beginning in 2013. LOFAR will complement the MWA by offering higher angular resolution observations of the Sun at meter wavelengths, but with lower dynamic range and imaging fidelity owning to its sparser *u*-*v* coverage.

6.2. *The Sun at Centimeter Wavelengths*

As reported by T. Bastian, significant progress has been made in commissioning the JVLA for solar observing, with the first solar science observations undertaken in late 2011. He is part of a team that has obtained the first ever dynamic imaging spectroscopy of a decimetric type III radio burst using the new system (Chen et al. 2013). Such bursts are an important diagnostic of impulsive magnetic energy release in the corona, but their exploitation for this purpose has been previously hampered by the lack of dynamic imaging capabilities. The high time and frequency resolution (100 ms and 1 MHz, respectively) and the broad frequency coverage (1-2 GHz) of the new JVLA observations enabled tracking of the nonthermal electron beam trajectories in the corona during the magnetic energy release that occurred in the aftermath of a flare. The new data imply that the spatial scale of the reconnection sites are tens of km or less and that the coronal medium is fibrous. The data further point to a highly fragmentary magnetic energy release process.

6.3. *Radio Emission and the Solar Cycle*

S. Cranmer raised the puzzle of why the sphere-averaged mass flux measured from the Sun is so constant, given that coronal heating varies by orders of magnitude over the solar cycle (and from point to point on the Sun). Part of the answer appears to be that there is a sort of "thermostat" through which the coronal temperature is kept roughly constant via the balance of heating conduction coming down from the corona, enthalpy flux flowing up, and local radiation losses. These would then conspire to keep the coronal temperature roughly constant even though coronal heating injection rates are varying considerably.

S. White noted that the changes in the solar radio emission that do occur with the solar cycle are dominated by bremsstrahlung emission (and some contribution from gyroresonance) and are much smaller than the variations detectable in X-rays. He consequently advised that the radio domain is probably not the best place to search for behavior analogous to the solar cycle in other stars. However, for stars covered by kilogauss magnetic fields (and where coronal temperatures reach as high as $\sim 10^7$ K), quiescent emission could conceivably become dominated by optically thick gyroresonant emission (a situation quite different from the solar case).

6.4. *The Failure of the Sun as a Role Model*

S. White pointed out several additional areas in stellar astrophysics where our own Sun provides frustratingly little guidance and insight for understanding other stars. For example, the solar wind is optically thin at all frequencies, and to date, no stellar wind from an active dwarf has been detected in the radio (but see also §7.2). For expected wind temperatures ($\sim 10^4$ K), extraordinarily high mass loss rates would be required (and these are not expected). This might change, however, if the wind/corona is in some cases much hotter ($\sim 10^7$ K). Another "disappointment" is that radio recombination lines have never been detected from the Sun. The presumed explanation is that these lines are too pressure broadened to see. V. Strelnitski (Maria Mitchell Observatory) suggested that a search for solar recombination lines in the infrared might be more fruitful, as masing may make these transitions more readily detectable.

Another puzzle pointed out by White is that on flare stars, the observed radio SEDs have generally been interpreted as gyrosynchrotron in order to produce the observed brightness temperatures. However, the flat spectral shapes are different from those seen on the Sun, and it is difficult to find a plausible spread in magnetic field strengths that can match the data.

6.5. *Future Prospects in Solar Radio Astronomy*

Prospects for new areas of discovery in solar radio astronomy were pointed out by several meeting participants. S. White described future solar instrumentation including the planned ultra-wide bandwidth Frequency Agile Solar Radiotelescope (FASR) envisioned to operate from 50 MHz to 20 GHz. FASR has repeatedly received strong endorsements but remains unfunded. In the mean time, White noted that solar astronomers are eagerly awaiting the commissioning of ALMA for solar work (expected in late 2012) in order to provide imaging capabilities for the study of the solar chromosphere at mm wavelengths. Another area where ALMA is likely to contribute to the understanding of solar emission pro-

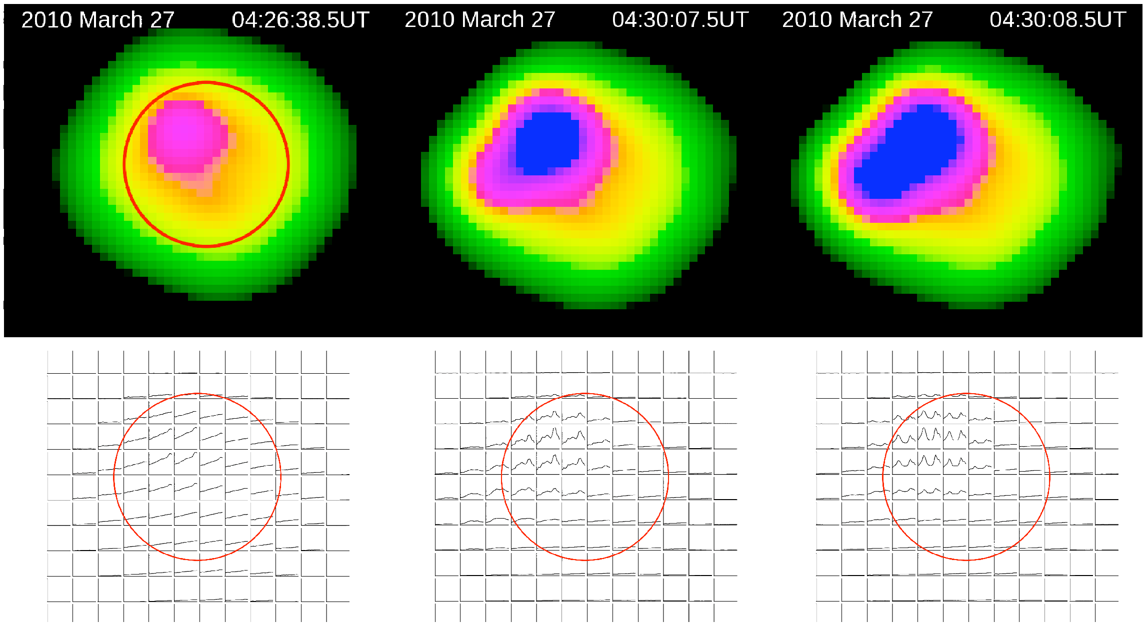

FIG. 2.— *Top row:* Single polarization images of the Sun at 193.3 MHz obtained with the MWA 32-tile prototype array on 2010 March 27. The data were averaged over a time of 1 second and a bandwidth of 0.8 MHz. The restoring beam was circular with a FWHM of 800″. Dynamic range is ∼2500. The red circle corresponds to the optical disk of the Sun. *Bottom row:* Spatially localized spectra across the disk of the Sun at times corresponding to the images in the top row. The bandwidth of each spectrum is 30 MHz. Spectra are shown for every third pixel, where each pixel is 100″ × 100″. From Oberoi et al. 2011.

cesses is by shedding insight into flaring previously observed in the 100-200 GHz range. As noted by White, the observed spectra show a rising component beyond 100 GHz and thus cannot be fit by gyrosynchrotron emission alone. A variety of explanations have been considered (positrons, inverse Compton, thermal, synchrotron), but none offers a satisfactory fit.

White pointed to spike bursts as examples of electron cyclotron maser emission from the Sun. Their nature remains poorly understood, and he hinted that further attention to these events might be prudent, given that they were responsible for a Global Positioning Satellite (GPS) outage in 2006.

S. Cranmer reminded us that the question of what drives the solar wind is still controversial—i.e., we do not yet understand how mechanical energy (convection) is transferred above the solar surface. One idea is that open magnetic flux tubes are jostled about by convective motions in the solar granulation, eventually dissipating in a kind of turbulence. A second idea is that open magnetic fields are always sitting in the vicinity of closed magnetic fields and that emerging closed structures are constantly interacting with the open structures, causing magnetic reconnections, thereby transferring mass and energy from the closed field to the open field.

As illustrated by White, D. Oberoi, and T. Bastian, dynamic imaging spectroscopy is opening a new frontier in solar science, enabling studies of solar (and stellar) radio emission with unprecedented levels of detail. However, creative new solutions are needed for managing such data sets, where effectively every point in the time and frequency domains yields a unique image of the Sun. Underscoring this, in the recent JVLA commissioning study of a solar flare described by Bastian (§6.2), 20,000 snapshots were produced *per second*, and this capability has already doubled thanks to a factor of two improvement in time resolution.

White noted that type II solar bursts have long been associated with coronal mass ejections (CMEs), although in his view, this association should be viewed with some skepticism, as examples of type II bursts have been seen without any obvious connection to a CME. R. Osten countered that several studies have supported such a link. It will be interesting to see if type II analogs are detected from other stars using the new generation of low frequency arrays (LWA, MWA, LOFAR), particularly if the correlation with CMEs can be verified. As pointed out by Osten, this could provide one means of directly observing mass loss from cool dwarfs, whose "steady" winds are generally too feeble to be directly detected ($\sim 10^{-14}\ M_\odot$ yr^{-1}). While CMEs are only a minor contributor to mass loss from the Sun, they may be more important for other types of stars, particularly active young stars.

Solar noise storms remain an enigma, in part because no counterparts have been identified at other wavelengths. They are known to sit over vigorous active regions, but how they manage to produce a steady flux of energetic electrons is unknown. Analogs to noise storms have also now been identified on other stars (e.g., RS CVn). White showed a dynamic spectrum (52-71 MHz) of a solar noise storm recently obtained with the LWA. However, noise storms are more often seen at higher frequencies, and a recent example detected from 1-2 GHz with the JVLA by Chen & Bastian (in preparation) was also presented.

7. STELLAR WINDS AND MASS LOSS

Virtually all stars are believed to be losing mass through stellar winds, although the rate of this mass loss varies by nearly 12 orders of magnitude across the H-R diagram. This mass loss impacts the evolution of the stars themselves, the star's surroundings, and ultimately, affects the evolution of the entire Galaxy. As we were reminded in the review by S. Cranmer, the key driving mechanisms for stellar winds include: (1) gas pressure; (2) radiation pressure; (3) wave pressure/shocks; (4) MHD effects (which may produce mass loss through CMEs or "plasmoids"). Molecular line emission (from cool giants) and free-free emission (from partially ionized winds of hot stars) are two ways in which radio observations have traditionally been used to study stellar mass loss.

7.1. *Hot Star Winds*

We were reminded by M. Güdel and S. Kwok that hot star winds are a case where radio observations led to a whole new concept in stellar mass loss. The winds from these stars are ionized and give rise to optically thick thermal emission in the radio. By observing at shorter and shorter radio wavelengths, one sees material closer and closer to the star. Classically, the flux density from these stars is predicted to scale as $S_\nu \propto (\dot{M})^{\frac{4}{3}}\nu^{0.6}$ where $\dot{M}$ is the mass loss rate of ν is the frequency. However, mass loss rates derived this way are systematically higher than those derived from other diagnostics (e.g., X-ray line asymmetries), implying that the wind is likely clumped, making its emission proportional to the square of the density.

Related to this theme, a poster by M. M. Rubio-Díez (Centro Astrobiologia, INTA-CSIC) focused on the reconciliation between the mass loss rates of OB star winds derived from a variety of tracers. Correctly accounting for density inhomogeneities is found to be crucial, and she emphasized the importance of sampling the entire wind using a range of tracers (including radio observations of the outermost wind region) for constraining models.

The current status of stellar wind theory was reviewed by S. Cranmer, who described a number of aspects of stellar wind physics that are important to keep in mind when interpreting observations. For example, he highlighted the effect of "gravity darkening" in fully radiative stars. Gravitational effects alone would predict more mass loss from the equatorial regions of stars, where centrifugal forces are maximized; however, gravity darkening actually reverses this trend (because the local effective temperature is much higher at the poles than at the equator), leading to enhanced polar mass loss and to the production of prolate, bipolar outflows. While gravity darkening likely cannot explain all such outflows, Cranmer suggested that it may be an important and overlooked effect in some instances.

Cranmer reminded us that stellar winds play a fundamental role in massive star evolution and that the fraction of the total mass returned to the ISM through winds vs. supernova explosions changes dramatically as a function of initial stellar mass. For ~8-10 $M_\odot$ stars, most of the mass return occurs in the subsequent supernova explosion; mass loss during the red supergiant phase becomes increasingly important for ~20-30 $M_\odot$ stars, while for $M_\star \gtrsim 30 M_\odot$, the Wolf-Rayet phase becomes dominant in the mass recycling.

Several puzzles persist concerning mass loss and winds from classical Be stars, including the formation mechanism for their "decretion" disks. Since these stars are rotating well below breakup speed, it remains unclear how their circumstellar gas acquires angular momentum, although non-radial pulsations are likely to be involved in providing the spin-up needed to effectively cancel gravity (e.g., Cranmer 2009). Cranmer noted that Be stars also lose mass through ionized polar winds, but the ionization source for these outflows is unknown. Unstable shocks are one possibility.

7.2. *Winds from Cool Dwarfs*

Constraining the driver of mass loss from cool dwarfs ($T_{\rm eff}$ $\lesssim$8000 K) has been notoriously difficult since the feeble winds from these stars tend to be too low to detect directly (see also §6.4, §6.5). This makes insights gleaned from the solar wind particularly important. Cranmer described recent theoretical work (Cranmer & Saar 2011) that for the first time provides physically motivated predictions for the stellar winds of late-type stars that enable prediction of mass loss rate directly from a star's fundamental properties (including rotational velocity). This work takes inspiration from recent progress in understanding solar wind acceleration by tracing the energy flux from MHD turbulence from a subsurface convective zone to its dissipation and escape through open magnetic flux tubes as a stellar wind. Results are a significant improvement over past semi-empirical correlations which could not reproduce star-to-star variations caused by differing rotation rates.

Cranmer stated that while stellar wind theory is typically successful to within an order of magnitude, one must keep in mind that applying these theories requires knowing considerable information about the star in question (e.g., mass, luminosity, age, rotational velocity, magnetic field strength, pulsation properties). Fortunately, as we heard at the meeting, radio observations of stars offer one means to constrain many of these parameters.

Finally, Cranmer raised the questions of whether "multi-thermal" stellar winds might exist, analogous to the multi-phase structure of the interstellar medium (ISM). Answers could come from, e.g., combining radio (and IR) observations of "cold" dust-forming gas with UV spectroscopy to probe warmer chromospheric gas.

7.3. *Winds from Red Giants*

E. O'Gorman (Trinity College Dublin) reminded us that despite decades of research, the driving mechanism of the winds from "ordinary" (non-pulsating) Red Giants remains a puzzle. Lying beyond the Linsky-Haisch dividing line (Linsky & Haisch 1979), these stars have minimal chromospheric emission, but instead exhibit slow, relatively dense, largely neutral winds where $V_{\rm terminal} < V_{\rm escape}$. This implies that most of the energy of the wind goes into lifting it out of the stellar gravitational potential, not the final wind kinetic energy. Since these winds have insufficient dust and molecular opacity for efficient radiative driving, and since mass-loss rates too high to be explained by pulsationally-driven wind models, and since hot wind plasma is absent (ruling out "coronal" type winds), some type of magnetically-driven wind is favored. However, many questions remain.

One key to constraining the wind driving mechanism is accurate characterization of the temperature and density structure of the wind. While these are poorly constrained by traditional ultraviolet observations, radio observations in the mm/cm can provide key insights, since the thermal continuum emission depends linearly on temperature. Another advantage of radio observations is that the opacity scales as roughly $\lambda^{2.1}$; consequently, longer wavelengths probe further out in the wind, effectively allowing multi-frequency observations to provide spatial information on objects that are unresolved. The drawback has been that Red Giants (whose centimetric emission stems from thermal free-free from the ionized component of the wind) are feeble radio emitters, making them too weak to detect at a wide range of radio frequencies—until now.

Thanks to the greatly expanded bandwidth of the JVLA, O'Gorman showed that it is now possible to obtain SEDs for nearby Red Giants over the full range of JVLA bands from 3 to 43 GHz. He presented results for two stars, α Boo (Arcturus) and α Tau (Aldebaran), and for the first time, complete frequency coverage was obtained for each star within a period spanning less than two weeks, thus mitigating effects of possible variability. Both stars were detected as point sources in all bands with flux densities ranging from 0.06 to 3.7 mJy, and the new measurements reveal discrepancies with existing models. To investigate the cause of this, O'Gorman plans to employ future modeling using a new hydrogen ionization code (which accurately treats the "freezing out" of the ionization balance in the wind) to provide new insights into temperature and density profiles of the winds as a function of radius.

8. EVOLVED STARS

Radio observations have long been recognized as a powerful tool for studying atmospheric physics, mass loss, and circumstellar chemistry during the late stages of stellar evolution. Not surprisingly, an entire day of the Radio Stars workshop was devoted to discussion of the latest developments in the study of red supergiants (RSGs), asymptotic giant branch (AGB) stars, and the evolution of the latter into planetary nebulae (PNe). Cepheid variables were also briefly touched upon. An overview talk by R. Sahai (Jet Propulsion Laboratory) set the stage for the discussion of this broad topic (see below).

8.1. *Red Supergiants*

Observations were presented at the workshop for a diverse set of red supergiants (RSGs; see also §8.2 and §8.9.2). B. Zhang (Max Planck Institut für Radioastronomie) described recent VLBA and VLA observations of NML Cyg, one of the most luminous RSGs in the Galaxy. Based on astrometric measurements of the H_2O masers over several epochs, he and his colleagues obtained a distance and proper motion consistent with this star being a member of the Cyg OB2 association (Zhang et al. 2012). Using the VLA, they detected the radio photosphere of the star at 43 GHz and measured a diameter of 44±16 mas. This result would imply an enormous size for the star (~70 AU for a distance of 1.6 kpc). Future JVLA measurements will be able to confirm this result and to significantly reduce the error bar on this measurement. A combination of the VLBA and VLA data also allowed accurate astrometric registration of the SiO and H_2O masers with the photosphere of the star for the first time, revealing a highly asymmetric distribution of masers that is inconsistent with past models of the source geometry.

A. Richards (Jodrell Bank) presented new 5.75 GHz imaging observations of Betelgeuse (α Orionis) obtained with the expanded Multi-Element Radio Interferometry Network (e-MERLIN) in 2012 July with ~180 mas resolution. While analysis was still ongoing as of the time of the meeting, initial results showed the presence of two emission peaks within the central image of the star, as well as emission "hot spots" with brightness temperatures in excess of 4000 K. Additionally, the data revealed evidence for a "plume" extending to the southwest, similar to what has been seen independently by other workers in optical interferometric imaging and CO imaging at mm wavelengths.

V838 Mon, famous for its light echo, erupted in a nova-like burst in 2002 and emerged as a $10^6\ L_\odot$ RSG star six months later. The star is believed to have formed as the product of a recent merger of two main sequence stars. How long its supergiant phase will last is a question being studied by S. Deguchi (Nobeyama Radio Observatory). Deguchi and his colleagues monitored the star for SiO masers from Nobeyama, first detecting the SiO v=1 and v=2, J=1-0 lines roughly 3 years after the 2002 outburst (Deguchi et al. 2005). Since then they have found the intensities of the lines to be decreasing gradually. Deguchi emphasized that continued monitoring of the SiO masers is important for providing insight into what fraction of SiO maser stars (and what fraction of RSGs) are likely to be merger products.

While most RSGs are field stars, Deguchi also described observations of SiO masers from RSGs in massive young star clusters, which can offer important laboratories for understanding RSG evolution. He and his colleagues have been using such observations to derive velocity dispersions for the clusters, as well as dynamical masses and kinematic distances (e.g., Fok et al. 2012). One surprising finding was that the masses of RSGs in massive clusters are found to be smaller on average than those of some well-studied RSGs such as VY CMa.

8.2. *Radio Photospheres*

K. Menten (Max Planck Institut für Radioastronomie) highlighted the promise of the JVLA and ALMA for the study of radio photospheres of red giants. He cited as examples the possibility to obtain more than an order of magnitude improvement in accuracy in the photospheric diameter of IRC+10216 compared with recent VLA measurements (Menten et al. 2012) and the ability to image star spots (if they exist) in the radio photosphere of Betelgeuse (see also §8.1). In the case of ALMA, he noted that study of the composition of the molecular photosphere will become feasible (see §8.9) and that the ~20% size variations in AGB stars due to pulsation are expected to be discernible. M. Reid (Harvard-Smithsonian Center for Astrophysics) also reminded us that existing observations of radio photospheres place stringent limits on the presence of regions of hot (~10000 K) gas at a few stellar radii in AGB stars, seemingly ruling out strong shocks in their extended atmospheres.

8.3. *Mass Loss on the Asymptotic Giant Branch*

8.4. *Mass Loss Rates and Geometries*

As pointed out by R. Sahai, a limitation of past studies that have derived mass loss rates for AGB stars using molecular line observations (primarily CO) is that they have relied on simple or analytical models in which some

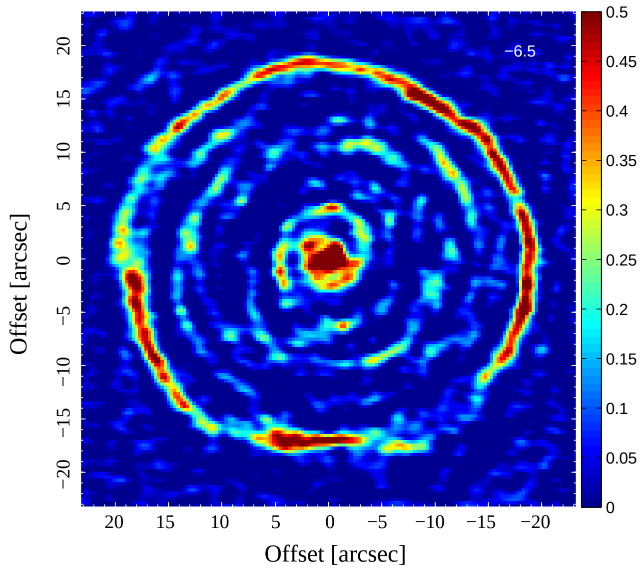

Fig. 3.— CO(3-2) emission at the stellar systemic velocity ($V_{\rm LSR} = -6.5$ km s^{-1}) from the circumstellar environment of the AGB star R Sculptoris, observed with ALMA during Cycle 0 (Maercker et al. 2012). The intensity scale is in Jy beam^{-1}.

kinematic temperature was assumed. Sahai highlighted as a major advance in the past few years the emergence of new studies that interpret molecular line data using full self-consistent radiative transfer and thermodynamic modeling (e.g., De Beck et al. 2010).

While the assumption of smooth, spherically symmetric outflows from AGB stars works reasonably well in many cases, it is also seen to break down in some instances. One spectacular example was presented by M. Maercker (European Southern Observatory), who showed data for the carbon star R Scl recently obtained with ALMA (Maercker et al. 2012). R Scl was known from previous *Hubble Space Telescope* imaging to be surrounded by a detached shell, thought to be the product of a thermal pulse. However, recent ALMA CO(3-2) observations revealed a surprise: a 3-D spiral pattern extending from the star to the detached shell (which is itself also detected in CO; Figure 3). The spiral pattern betrays the presence of an unseen companion that is sculpting the outflowing AGB wind. Imprinted in this spiral pattern is a historical record of the stellar mass loss history since the last thermal pulse.

Maercker showed that from simple geometric arguments alone it is possible to derive the orbital period of the binary, the wind expansion velocity as a function of time, the evolution of the mass loss rate with time, and the age of the detached shell. The spherically symmetric shape of the detached shell also constrains the pulse duration to be much shorter than the binary orbital period. One curiosity was that no evidence for deceleration of the shell was seen, as would be expected as a consequence of interaction with debris from previous mass loss. Maercker's data set represents the first *observational* constraints on the pre- and post-thermal pulse state of an AGB star; until now, our existing understanding of thermal pulses has been essentially theoretically driven. This is significant since nucleosynthetic yields from AGB stars depend critically on the duration and frequency of thermal pulses.

S. Kwok showed another example of distinctly non-spherical structures in the circumstellar envelope (CSE) of the carbon star CIT 6. Employing spatiokinematic modeling, a recent study by Kwok and his colleagues (Chau et al. 2012) unveiled the presence of several incomplete shells. Similar features have also been previously seen in IRC+10216. These partial shells may be due to time- and space-dependent mass loss, but the underlying driving mechanism remains unclear.

8.4.1. *Probing the Complete History of AGB Mass Loss*

R. Sahai highlighted the challenge of determining the total mass of CSEs of evolved stars given that commonly used molecular diagnostics constitute only trace components of the CSE and do not sample the entire envelope. One means of addressing this question is through observations of circumstellar atomic hydrogen. T. Le Bertre (Observatoire de Paris) described the range of advantages the H I 21-cm line offers for studying the extended portions of CSEs and hence the extended mass loss history of AGB and related stars. Because H I is not readily destroyed by the interstellar radiation field, it can be used to probe the circumstellar ejecta to much larger distances from the star compared with commonly used molecular tracers such as CO, thereby tracing a larger fraction of the stellar mass loss history ($> 10^5$ yr). As a spectral line, it also provides valuable kinematic information. Moreover, because in most instances the hydrogen is optically thin ($h\nu/kT << 1$), this implies that H I measurements can be directly translated into a measurement of the mass in atomic hydrogen (assuming the distance is known).

Le Bertre described an ongoing program at the Nançay Radio Telescope (NRT) that has now surveyed more than one hundred AGB and related stars in the H I 21-cm line (Gérard et al. 2011). The target stars span a range in chemistries, mass loss rates, variability classes, and other properties. Detection rates are high (∼80%) for semi-regular and irregular variables, but lower for Miras despite their on-average higher mass loss rates. This paradox may be due to the generally lower temperatures of the Miras, which may lead to more hydrogen in molecular form or atomic hydrogen that is too cold to be readily detected in emission.

One discovery from the NRT studies is that the observed H I line profiles are frequently narrower than seen in CO and in some cases have a two-component structure that includes a broader pedestal. This finding can be explained by a freely expanding wind that is slowed down at large radii by the surrounding medium (e.g., Le Bertre et al. 2012). The narrow line component then results from a highly extended (∼0.1 to 1.0 pc), quasi-stationary shell of material that accumulates between a termination shock and the ISM interface, while the broader component is the counterpart to the freely expanding wind at smaller radii. Another finding is that the H I line centroids of the detected stars are frequently found to be displaced toward zero Local Standard of Rest velocity, indicative of interaction between the CSE and the local ISM owing to the star's space motion.

Following Le Bertre's talk, I described an ongoing pro-

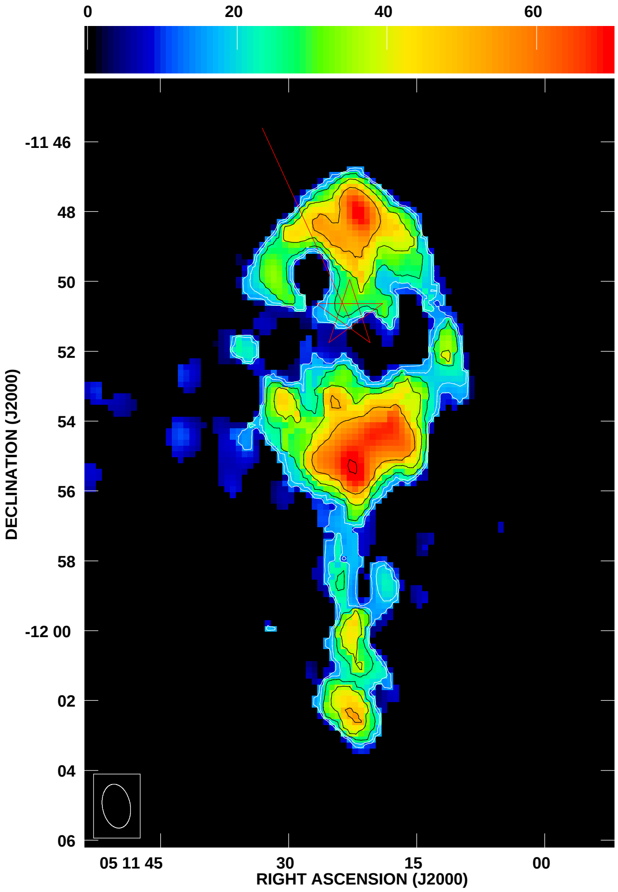

Fig. 4.— H I total intensity image of the AGB star RX Lep from Matthews et al. 2013. The star symbol indicates the stellar position, and the red line indicates the direction of space motion. The projected extent of the H I shell and tail is ∼0.7 pc in the north-south direction. The intensity scale has units of Jy beam^{-1} m s^{-1}. The synthesized beam is $\sim 76'' \times 48''$.

gram with the VLA and JVLA to image circumstellar H I. To date, we have successfully imaged more than a dozen red giants (e.g., Matthews et al. 2013). In all cases we find clear evidence that the properties of the extended CSE are set by both the properties of the star itself and by the interaction between the star and its interstellar environment. One manifestation of this is the discovery of several examples of H I "tails" up to a parsec or more in extent, trailing the motions of the stars through space (Figure 4). These tails are predominantly seen associated with stars with high space velocities ($V_{\rm space} \gtrsim$60 km s^{-1}) and arise from ram pressure on the circumstellar ejecta as these mass-losing stars move supersonically through the ISM. In some instances, we have detected velocity gradients along these H I wakes that arise from deceleration of the gas through interaction with the ISM; such measurements in turn supply a means of age-dating the mass loss history of the star, confirming that the H I traces $> 10^5$ years of stellar mass loss (e.g., Matthews et al. 2011). For stars with lower space velocities, interaction with the local ISM is also seen manifested through the presence of detached H I shells, formed when the outflowing wind is abruptly slowed at a termination shock. The presence of these shells in our images confirms the picture first inferred from the two-component NRT line profiles described by Le Bertre. One example is our recent discovery of an H I shell with a diameter of ∼0.24 pc surrounding Betelgeuse (Le Bertre et al. 2012). This result was showcased in a poster presented by Le Bertre.

8.5. *Mass Loss from Cepheid Variables*

Despite the importance of Cepheid variables as extragalactic distance indicators and as cornerstones to our understanding of the evolution of intermediate mass stars, a puzzling "Cepheid mass discrepancy" has persisted for several decades: the masses inferred from stellar evolution models are systematically higher than those derived from stellar pulsation (or binary orbital dynamics when available). Mass loss has long been proposed as a solution to this discrepancy, but direct empirical confirmation has remained elusive. I described how new insights are coming from observations of Cepheids in the H I 21-cm line. Using the VLA, we recently detected an extended (∼1 pc across) H I nebula surrounding the position of the Cepheid archetype, δ Cephei (Matthews et al. 2012). The position and head-tail morphology of this emission are consistent with a remnant of recent/ongoing mass loss from δ Cephei. Based on these data, we have derived a mass loss rate $\dot{M} \approx (1.0 \pm 0.5) \times 10^{-6} M_{\odot}$ yr^{-1} and an outflow velocity of $V_{\rm out} \approx$35 km s^{-1} (the first ever measured for a Cepheid). Analysis of data from a JVLA survey of additional Cepheids in the H I line is ongoing.

8.6. *Circumstellar Masers*

8.6.1. *Observations*

S. Deguchi reviewed the topic of circumstellar masers from an observational perspective. He reminded us that in addition to the maser species commonly observed in the atmospheres of oxygen-rich evolved stars (OH, H_2O, SiO), masers are also seen in carbon-rich stars, including HCN, SiS, and CS. The latter are typically weaker than the masers in oxygen-rich stars, and consequently have been relatively little studied. He also underscored that stellar masers are not just limited to AGB stars, but also occur in a variety of more "extreme" stellar environments where they can provide important new insights into sources ranging from RSGs (§8.1) to water fountains (§8.8.5) to novae (§10.1).

Two poster contributions presented new results on the molecular masers in Mira (o Ceti). G. McIntosh (University of Minnesota, Morris) presented long-term monitoring data from the Haystack and Mopra telescopes of multiple SiO transitions. Evidence was seen for correlations between the velocity range of emission and stellar phase. R. Zizza (Wellesley College) presented a complementary study that showcased six epochs of simultaneous VLA imaging data of the SiO v=1, J=1-0 and 22 GHz H_2O masers in Mira. Consistent with McIntosh's results, the integrated flux density of both the SiO and H_2O masers is seen to correlate with the stellar phase-dependent variations in the optical light. These data also represent some of the first ever concurrent imaging of the SiO and H_2O masers in an AGB star, providing direct information on their relative locations in the stellar envelope.

Interferometric imaging of the water masers in the atmospheres of AGB stars (including Zizza's VLA study of Mira) have shown that these masers tend to lie in "shells" with radii $r \sim$5-30$R_{\star}$. A. Richards showed that this relationship also holds for RSG stars despite the fact that the stellar radius grows from ∼1 AU for AGB stars to roughly an order of magnitude larger for RSGs.

Theoretically, brighter water maser clumps in evolved stars are expected to exhibit smaller beamed sizes (assuming they are spherical). However, Richards described recent work based on MERLIN observations in which she and her colleagues identified two stars in which this prediction is violated. The two stars exhibit the most extreme water maser variability in their sample, suggesting that masers arise instead from shocked slabs (Richards et al. 2011). Their recent work also shows that in RSGs, water maser clouds can be traced for upwards of 5 years, while in AGB stars the lifetimes tend to be less than 2 years. These survival times are comparable to sound crossing timescales but much less than the maser shell crossing times. While results from a combination of interferometric and single-dish monitoring do show velocity peaks in the spectra vanishing and re-appearing, Richards proposed that this was due to the masers turning off from turbulence or beaming effects, not the actual destruction and reformation of clouds, since there is not an obvious mechanism by which this could occur.

Richards also presented observations of several stars where numerous individual water maser clouds are seen to brighten/dim in lockstep when observed at subsequent epochs. Such correlations visible on the timescale of weeks seems to rule out shocks as responsible for the fluctuations, since the shock propagation velocities required would have to be unphysically high. Instead this observation seems to point toward a radiatively driven pumping mechanism. Finally, Richards is finding evidence that water maser cloud size, R_c, is proportional to the stellar radius [$R_c \sim (0.7 \pm 0.3)R_\star^{1.0\pm0.1}$]. One interpretation is that convection cells determine the cloud size.

8.6.2. *Maser Theory*

V. Strelnitski noted that the fundamentals of the theory of maser amplification in astrophysical sources were developed in the late 1960s and early 1970s (soon after the discovery of cosmic masers) and that advances in maser theory have since somewhat stagnated. His review talk nonetheless pointed out some new developments and also highlighted several concepts that are crucial for astronomers to be mindful of as they attempt to gain physical insights from maser observations.

One point emphasized by Strelnitski is that a maser requires a system with more than two population levels (a two-level system cannot sustain the population inversion required to produce a maser since its excitation temperature always remains positive). This has consequences for assessing when a maser "thermalizes", as one cannot simply compute the thermalization condition for a maser by using a two-level approximation; doing so may produce large errors in the maximum allowed gas densities where a maser may occur. For example, if collisions participate in pumping, thermalization will occur at much higher densities than in a two-level system.

Concerning the characterization of maser pumping mechanisms, Strelnitski stressed the need to consider not just the "source" (i.e., a high-energy reservoir from which energy is extracted), but both the *source* and the *sink* (the low-energy reservoirs to which energy is transferred). Thus maser pumping is never just "collisional", but e.g., "collisional-collisional" or "collisional-radiative". He cited the latter as being the most likely to occur in CSEs, with collisions pumping the molecules to higher levels and spontaneous emission creating the "sink" that completes the cycle.

Strelnitski cited several areas where additional work would be valuable. One example is extending the use of masers as tracers of turbulence. A promising application may be to the study of water fountain sources (§8.8.5). He also advocated work on the development of methods of extraction of the principal pumping cycles in numerical calculations, which will enable recovery of the details of maser pumping schemes (e.g., Gray 2007). At present, most numerical schemes typically provide only a final solution, and no details on the population flow are stored.

8.7. *Magnetic Fields in Evolved Stars*

The number of AGB (and post-AGB) stars whose magnetic fields have been characterized is small but rapidly growing. W. Vlemmings (Onsala Space Observatory) provided an overview of this topic and the observational techniques being employed to probe magnetic fields and their evolutionary roles in evolved stars.

To date, the bulk of measurements of magnetic field *strength* in evolved stars and PNe have been derived from circular polarization (Zeeman splitting) measurements of OH, H_2O, and SiO masers, or in a few cases, Zeeman splitting of non-masing molecular lines. Constraints on the *shape* of the magnetic field come from linear polarization measurements of masers as well as observations of aligned dust grains and molecules (via the so-called Goldreich-Kylafis effect).

As described by Vlemmings, recent measurements of SiO masers in oxygen-rich stars (which lie at radii $r \sim 2R_\star$) suggest magnetic field strengths of ∼1-10 G, with the caveat that there are other mechanisms that might explain the observed polarization without requiring such a strong field. Water masers (lying between ∼50-80 AU) reveal field strengths B ∼0.1-2 G, and OH masers (lying at ∼100-1000 AU) imply B ∼1-10 mG. For carbon-rich stars, a handful of measurements of CN at r ∼2500 AU yield B ∼7-20 mG. The radial dependence of the magnetic field is still not well constrained owing to uncertainties in the location of the masers relative to the central star, and observations are consistent with either r^{-2} (solar-type) or r^{-1} fall-offs. Despite this uncertainty, the results to date point to magnetic fields dominating the energy densities of AGB stars out to radii of ∼50 AU.

Vlemmings reported new VLBA measurements of H_2O masers in 3 AGB stars which point to field strengths of a few hundred mG, consistent with previous measurements of other AGB stars. They have also detected for the first time in AGB stars weak linear polarization in the H_2O lines (at the ∼1% level; Leal-Ferreira et al., 2012a). Previously linear polarization of the H_2O masers had been detected only in PPNe and star-forming regions. For the proto-planetary Rotten Egg Nebula (see also §8.8.3), Vlemmings and colleagues measured B ∼45 mG and derived an extrapolated magnetic field strength of ∼3 G. This represents one of the first magnetic field measurements around a known binary system (Leal-Ferreira et al. 2012b).

Vlemmings described recent developments in the study of magnetic fields using non-masing (thermal) lines via the Goldreich-Kylafis effect. This approach complements maser measurements by more comprehensively probing the entire CSE. Demonstrating the feasibility of this method, he showed new Submillimeter Array (SMA) polarization measurements of several thermal lines toward AGB stars including IRC+10216 (Girart et al. 2012), IK Tau (Vlemmings et al. 2012) and χ Cyg (Tafoya et al., in preparation). In all cases, evidence of non-radial linear polarization is observed, consistent with the presence of large-scale magnetic fields.

N. Amiri (University of Colorado, Boulder) reported recent VLBA measurements of the SiO masers and their polarization properties in the OH/IR star OH 44.8−2.3. This is the first OH/IR star whose SiO masers have been studied with Very Long Baseline Interferometry (VLBI) resolution. The SiO masers in OH 44.8−2.3 were found to lie in a ring pattern with a radius comparable to those measured in Mira variables (Amiri et al. 2012). This result is a surprise, since the central star is expected to be much larger than an ordinary Mira. The maser ring also showed high fractional linear polarization (up to $\sim$100%) and a geometry consistent with a dipolar field. Gaps in the SiO ring as well as an elongation in the OH masers found in archival VLA observations reinforce this interpretation and suggest that magnetic fields may impose a preferred outflow direction in the CSE. This deviation from spherical symmetry is of particular significance, as OH/IR stars are thought to be nearing the transition to the PN stage.

Despite impressive progress, Vlemmings emphasized that much work remains to be done in characterizing magnetic fields and their role in late stellar evolution, and measurements of larger samples of stars will be critical for answering many of the outstanding questions. These include the ubiquity of magnetic fields, the impact of binarity on the magnetic field, the dynamical importance of the field, their role in AGB mass loss, and the origin of the field itself (e.g., a single star dynamo, a binary star or heavy planet, or disk interaction).

8.8. *The Road to Planetary Nebula Formation*

8.8.1. *The Origin of Non-Spherical Geometries*

Less than 5% of planetary nebulae (PNe) appear spherical, and the origin of the spectacular diversity of morphologies of PNe has remained a topic of vigorous research for decades. R. Sahai summarized results to date that point toward the mechanism responsible for shaping PNe becoming operational well before the PN phase itself—either in the post-AGB phase or possible very late in the AGB. S. Kwok also reminded us that one of the reasons radio observations of PNe are particularly valuable is that the bulk of their mass lies beyond what can be traced via optical light.

As described by Sahai, the collimated fast winds/jets that appear during the late AGB/post-AGB are believed to be the primary agent shaping PNe, although dusty equatorial tori may also help to confine the flows. Sahai noted that the fast bipolar outflows of proto-planetary nebulae (PPNe) have a large momentum excess ($L/c << dM/dt \times V_{\rm exp}$), implying the winds cannot be radiatively driven. Here L is the stellar luminosity, c is the speed of light, dM/dt is the mass flux and $V_{\rm exp}$ is the expansion velocity of the wind. The driving mechanism of these outflows thus remains unclear. J. Sokoloski (Columbia University) also pointed out that several symbiotic stars (which are known binaries) exhibit morphologies similar to PNe, offering additional support for the idea that binarity is a key shaping factor.

Sahai described a recently published survey of mass loss from a sample of post-AGB stars and young PNe using data from Owens Valley Radio Observatory (Sánchez Contreras & Sahai 2012). In total, 24 of 27 targets were detected in at least one CO transition, including 11 for the first time. Asymmetries and velocity gradients were seen to be the norm, with broad, high-velocity line wings indicative of fast outflows in more than 50% of the sample.

D. Tafoya (Onsala Space Observatory) presented a poster describing results from a study of two "water PNe", which based on the presence of water molecules, are believed to be in the very earliest stages of the PN phase. Such objects therefore offer an opportunity to study the development of bipolar PN morphologies. These objects are sufficiently young to still possess their molecular envelopes from the AGB mass loss phase. The source IRAS17347-3139 was detected with the SMA, and the ^{12}CO emission was found to exhibit three components; a slow extended component ($\sim$30 km s^{-1}) and two high-velocity compact components ($\sim$150 km s^{-1}). The slow component is roughly spherical and likely originated during the AGB, while the high-velocity components may be part of a precessing bipolar wind.

8.8.2. *The Origin of Dusty Equatorial Components*

R. Sahai cited the origin of dusty equatorial components as one of the greatest puzzles concerning post-AGB stars and PNe. This includes both "dusty waists" with sizes $\sim$1000 AU seen in PPNe and $\lesssim$50 AU circumbinary disks surrounding binary post-AGB stars. Recent work (Sahai et al. 2011) shows sub-mm excesses in both classes of objects, implying the unexpected presence of large grains. The long formation timescales required for these large grains place constraints on the age and formation of the dusty equatorial regions.

8.8.3. *Distance Measurements to Planetary Nebulae*

Accurate distance determinations for PPNe are crucial for constraining their evolution and fundamental parameters. Y. Choi (Max Planck Institut für Radioastronomie) described VLBA parallax and proper motion measurements of the water masers associated with OH 231.8+4.2 (also known as the "Rotten Egg" nebula), a PPN with a bipolar optical morphology and a binary central star. The resulting distance has an accuracy of better than 2% (1.54$\pm$0.02 kpc; Choi et al. 2012). Her team found blueshifted and redshifted components to the north and south, respectively, with a velocity separation of $\sim$20 km s^{-1}. Thus the outflow traced by the H_2O masers is consistent with an outflow from the central AGB star. This contrasts with observations in CO and other tracers previously measured at larger distances from the central star, where velocity differences between the two lobes are an order of magnitude higher.

8.8.4. *The Coldest Object in the Universe*

The PPN known as the Boomerang has been referred to as the "coldest object in the Universe" after a study by Sahai & Nyman (1997) showed that the kinematic temperature of the CSE is less than 2 K due to adiabatic expansion and a mass-loss rate that is sufficiently high ($\sim 10^{-3}$ $M_{\odot}$ yr^{-1}) to makes the CO(1-0) line optically thick to heating by the cosmic microwave background. Sahai presented new ALMA CO(1-0) and (2-1) observations of this object that reveal a bipolar outflow with the same orientation as the outflow previously seen in the optical. Evidence for a dense central waist (with indications of mm-sized grains) is seen along with lobes that exhibit a bubble-like structure. Weak, patchy absorption from the ultracold shell is also visible, together with patchy emission on the periphery of the shell. The latter provides the first direct evidence of grain photoelectric heating in an AGB star's CSE.

8.8.5. *Water Fountain Sources*

Water fountain sources are post-AGB stars (or very young PNe) with 22 GHz water maser emission spread over large velocity ranges, indicating high-velocity outflows (>100 km s^{-1}). Roughly ten examples of this class are presently known. S. Deguchi described recent VLBA observations of the H_2O masers in one example, IRAS18286-0959, where he and his colleagues identified two bipolar precessing jets that form a double helix structure (Yung et al. 2011) . This is almost certainly the hallmark of a binary, reinforcing the long-suspected link between water fountain sources and binarity. However, it remains unclear where the jets are launched (e.g., in an accretion disk around a compact object, the atmosphere of the post-AGB star, or both).

8.9. *Circumstellar Chemistry*

8.9.1. *Overview*

To date, roughly 80 molecular species have been detected in the CSEs of evolved stars. As noted by S. Kwok, circumstellar environments are particularly valuable laboratories for studying chemical synthesis and processes; the energy input from the central star is typically well constrained, there is a high level of symmetry, and quantities like density and temperature can be characterized as a function of radius more readily than in many other types of environments. Further, we have the added dimension of constraints on the evolutionary timescales involved.

K. Menten provided a comprehensive overview of the study of the chemistry of the envelopes of AGB stars and supergiants, highlighting some of the many advances in this subject expected to emerge thanks to the combination of bandwidth, sensitivity, spatial resolution afforded by new facilities, particularly ALMA and the JVLA. As noted by Menten, one of the greatest contributions anticipated from ALMA for the study of evolved stars will be the opportunity for the first time to study their *entire* molecular envelopes. In particular, ALMA's ability to study molecules using imaging observations at widely different spatial resolutions will be critical for disentangling chemistry and excitation conditions throughout the envelope and building up a picture of its evolution as a function of radius. While the SMA has already made some important contributions in this area, it is able to observe mostly high-excitation lines, whereas ALMA will additionally provide access to low-excitation lines. This will permit the study of the composition of the molecular photosphere, element depletion during dust formation, the acceleration of the envelope, and the photochemistry of the outer envelope. Importantly, the angular resolution of ALMA ($<0''.5$) will allow for the first time studies of the chemistry of the inner envelopes (including the molecule formation zones) on scales previously only accessible to maser observations.

Menten drew attention to the surprising detection of NH_3 in the CSEs of several AGB stars and supergiants (both O-rich and C-rich), with abundances exceeding those predicted by chemical models by many orders of magnitude (Menten et al. 2010). The wide bandwidth capabilities of the JVLA, which will allow simultaneous imaging of ten different NH_3 transitions, should be instrumental in gaining new insight into this puzzle by providing far better constraints on models.

Advanced new software tools will play a crucial supporting role in the interpretation of new sub-mm data sets. W. Vlemmings presented a poster advertising ARTIST (Adaptable Radiative Transfer Innovations for Submillimeter Telescopes), a next generation model suite that allows multi-dimensional radiative transfer calculations of dust and line emission and their polarization properties.

Finally, Kwok pointed out that expanded access to the sub-mm spectrum will permit the study of many potentially important molecular lines that have previously received little attention in the study of CSE chemistry. Examples include O_2 and molecular ions.

8.9.2. *Line Surveys*

Thanks to technological advances, the last several years have seen a rapid growth in spectral line imaging surveys—a trend that is only expected to grow as the full capability of instruments like ALMA and the JVLA come on line and the body of supporting laboratory work grows. As noted by M. Claussen (National Radio Astronomy Observatory), spectroscopic imaging surveys bring a number of advantages for the study of CSEs compared with single-dish line surveys. These include the ability to study molecular/isotopic abundances as a function of radius, to infer excitation temperature of molecules based on their location in the CSE, to identify molecules linked with dust formation, to probe physical conditions as a function of radius (by looking at different transitions of the same molecule), and to search for complex structures in the line emission distribution (e.g., §8.4).

Claussen described an ongoing line survey of the nearby carbon star IRC+10216 in the 18-26.5 GHz and 18-50 GHz ranges being undertaken in conjunction with JVLA commissioning efforts. Despite the large number of previous single-dish line surveys of IRC+10216, the 18-50 GHz band had never before been surveyed. The JVLA study complements the recent mm/sub-mm surveys of this star by Patel et al. (2009, 2011) in the 294-355 GHz range using the SMA, which detected and imaged more than 400 lines with $3''$ resolution. Importantly, the JVLA provides access to lower J rotational transitions of hydrocarbon molecules.

As described by K. Young (Harvard-Smithsonian Center for Astrophysics), one of the most important re-

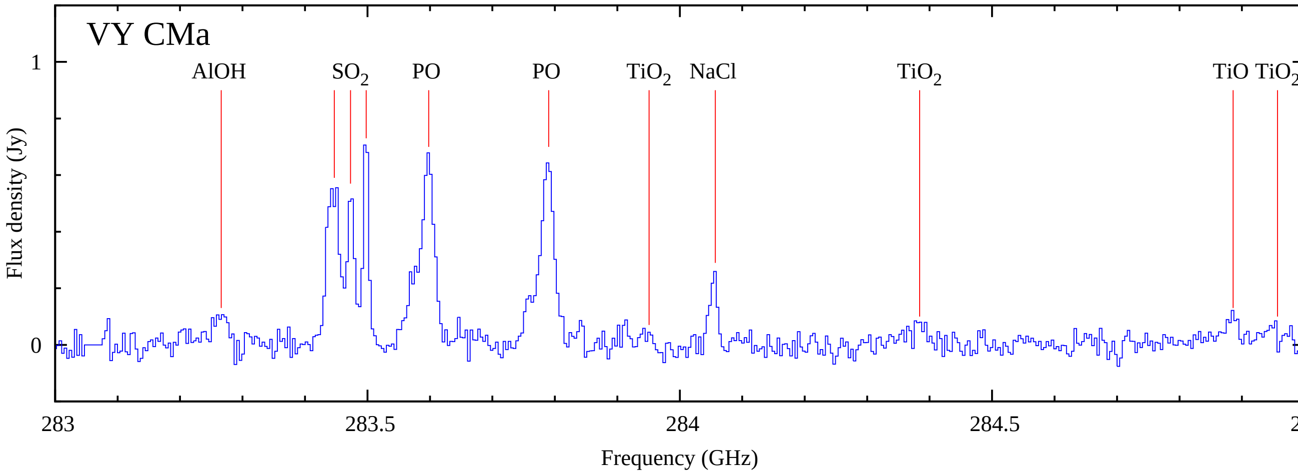

FIG. 5.— Detail of a portion of the 279-355 GHz spectrum of the red supergiant VY CMa obtained with the SMA by Kamiński et al. 2013.

sults from the Patel et al. survey was the discovery of a significant population of narrow line features (FWHM$\sim$8 km s^{-1}) having widths significantly smaller than twice the outflow velocity from the star ($2V_{\rm exp}$ $\approx$30 km s^{-1}). A significant fraction of these narrow lines arose from unidentified species, although most are suspected to be vibrational lines of common molecules like HCN, SiS, and SiO_2 for which the vibrational spectrum has not yet been measured (or not yet been made available). Young presented results from a new survey aimed at better characterizing these narrow lines using high-resolution ($\sim$0$''$.3) observations with the e-SMA (i.e, the SMA in combination with the Caltech Submillimeter Observatory and the James Clerk Maxwell Telescope). The survey employed a tuning that covered 31 of the narrow lines detected by Patel et al. Twenty-one of these were detected with the e-SMA while the emission regions giving rise to the remainder appear to have been resolved out.

A key result of the new e-SMA survey of IRC+10216 was the finding that the velocity widths of the majority of the detected narrow lines increase with increasing distance from the central star. Furthermore, Young showed that the trend seen in the change in line profile shape as a function of radius is inconsistent with a constant acceleration model. A linear acceleration model provides an improved fit, although at present the signal-to-noise ratio of the data is insufficient to distinguish between various more complex acceleration profiles.

Young stressed that analyses of this type are particularly important in the case of carbon-rich stars, since these stars lack the strong maser transitions of oxygen-rich stars (that more readily enable sampling the acceleration region of their envelopes). The acceleration zones of carbon-rich versus oxygen-rich stars may also differ owing to the different chemistries of their dust. New mm/sub-mm interferometers are expected to provide a boon to this type of study by enabling resolution of the acceleration zones of many nearby evolved stars.

To date, only about one-fourth of the molecular species identified in circumstellar environments have been seen toward oxygen-rich stars. Furthermore, until now, the only dedicated, unbiased line survey of an evolved star targeted carbon-rich IRC+10216. However, two workshop speakers presented results from new spectral surveys of oxygen-rich stars (one AGB star and one supergiant).

T. Kamiński (Max Planck Institut für Radioastronomie) described the ongoing analysis of line survey data in the 279-355 GHz range obtained with the SMA on the peculiar oxygen-rich RSG VY CMa, one of the largest stars in the Galaxy (Kamiński et al. 2013; Gottlieb et al., in preparation). He reported the detection of a total of 210 spectral features, all but 15 of which have been identified. Roughly half of the lines in the spectrum are sulfur compounds, a signature of shocks. Additionally, both TiO and TiO_2 were detected (Figure 5). TiO is extremely rare in the CSEs of evolved stars and has never before been detected in the radio, while TiO_2 has never been previously detected in an astronomical source (Kamiński et al. 2013). These molecules have been suspected as being important in dust formation in oxygen-rich evolved stars. A problem, however, is that in VY CMa the temperatures derived for both TiO and TiO_2 are far lower than model predictions. One solution could be that dust is forming in the hotter inner envelope, while the observed the molecules are the products of dust *destruction* (e.g., due to convective activity and shocks). In the future, the higher resolution of ALMA should be able to provide insight into this question.

A presentation by E. De Beck (Max Planck Institut für Radioastronomie) (delivered in absentia by M. Maercker) described results of an SMA survey of the oxygen-rich AGB star IK Tau in the same 279-355 GHz range as the IRC+10216 survey described by Kamiński. Approximately 200 lines have been identified. These include lines from molecules such as PN that have never before been seen in O-rich AGB stars. Also seen are dust-related species such as AlO, sulfur-bearing molecules (possibly indicating shocks), and multiple isotopologues of several species which are expected to be vital in constraining nucleosynthesis inside the star.

The results described by Claussen, Young, Kamiński, and De Beck underscore the importance of expanding unbiased line surveys (particularly line imaging surveys) to evolved stars spanning a broader range of chemistries and mass-loss rates. However, it was pointed out that a challenge to the analysis and interpretation of such data sets will be accurate *continuum subtraction*. As illustrated by K. Menten, regions of the spectrum that once looked like "continuum" are now seen to be rife with weak lines when observed with sensitive new instruments (e.g., Figure 5). S. Kwok pointed out that this may limit our ability to capitalize on improvements in sensitivity to find new, more complex molecules. While this is less of a problem in the JVLA bands compared with in the mm/sub-mm, accurate continuum subtraction is also critical in the former case since, as noted by Claussen, the continuum can otherwise be bright enough to render many weak lines invisible.

9. RADIO STARS AS TOOLS FOR MEASURING THE SCALE OF THE MILKY WAY

9.1. *The Distance to the Pleiades*

The Pleiades open cluster has long served as a benchmark for the determination of the distance to stellar clusters through main sequence fitting. As such, it serves as a critical first step in the cosmological distance ladder. However, the *Hipparcos* distance to the cluster is $\sim$10% smaller than that derived from other methods, leading to uncertainties of $\sim$0.2 magnitude in defining its Zero Age Main Sequence, and consequently throwing into flux theoretical models of young stars. C. Melis (University of California, San Diego) described an ongoing program to resolve this discrepancy using VLBI astrometric measurements of Pleiades members (Melis et al. 2012).

Melis and colleagues identified a sample of ten radio-bright stars in the Pleiades through a targeted survey of its most X-ray-bright members ($L_X \gtrsim 10^{30}$ erg s^{-1}). Most, if not all, of the targets so selected have turned out to be binaries. The target stars are weak ($\sim 100\mu$Jy) requiring use of a high sensitivity array comprising the VLBA, the Green Bank Telescope (GBT), Effelsberg, and Arecibo, and 900 hours of observations over the course of two years will be needed to complete this study. The outcome will be absolute parallaxes for ten Pleiades members with 1% precision. One indirect outcome may also be clues as to how the presence of a companion affects the radio luminosity of young stars. A possibility suggested by Melis is that the companion disrupts the tidal locking to the disk during the protostellar phase, preventing the stars from being spun down.

9.2. *Mapping the Structure of the Milky Way*

Our vantage point within the Milky Way Galaxy has long posed a severe challenge to astronomers attempting to measure its size scale and spiral structure. M. Reid described how new VLBI measurements of masers from young massive stars, compact H II regions, and evolved supergiants are providing fundamental new insights into these questions.

Reid pointed out that thanks to current calibration techniques, the accuracy of parallax measurements from VLBI techniques ($\sim 10\mu$as) already meets or exceeds that expected from the *GAIA* optical astrometric space mission. A further unique advantage is that only with radio wavelength VLBI techniques can such measurements be made in the plane of the Milky Way where extinction is severe, thus permitting measurements of the spiral structure.

Reid described recent results from the ongoing BeSSeL program, a VLBA key project to map the Milky Way's

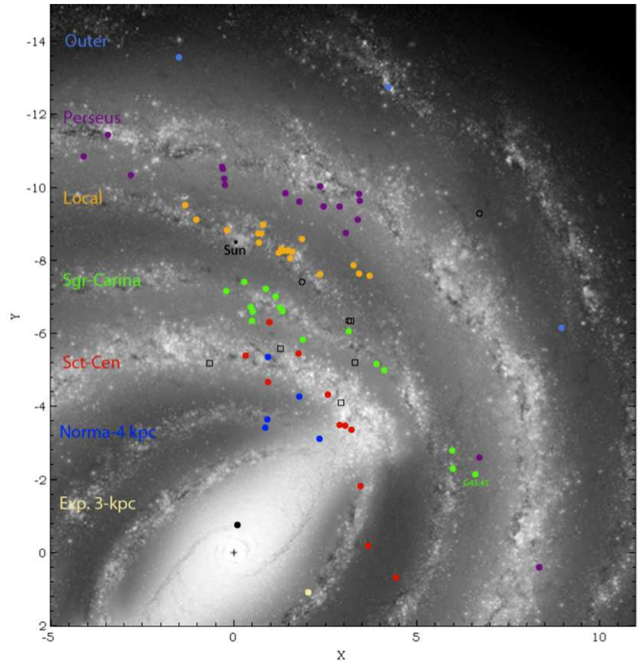

FIG. 6.— Locations of massive star forming regions with H_2O or CH_3OH maser parallaxes measured by the VLBA (the BeSSeL Survey), VERA, and the EVN, overlaid on an artist's conception of the Milky Way from R. Hurt (NASA/JPL-Caltech/SSC). Assignments to different spiral arms are based on CO longitude-velocity data and are indicated by the different colors. Image courtesy of M. Reid.

structure. This program (with Reid as Principal Investigator) was awarded more than 5000 observing hours over a five year period to accomplish this goal through the measurement of hundreds of parallaxes and proper motions of H_2O and CH_3OH masers. Observing began in 2010, and $\sim$70 sources have been observed so far, yielding $\sim$60 parallax measurements. Measurements are also being obtained with the European VLBI Network (EVN) and the VLBI Exploration of Radio Astronomy (VERA) array.

Results to date are consistent with the Milky Way having four major gaseous spiral arms plus additional minor ones near its bar Figure 6). The data permit characterization of the pitch angle of these arms, yielding values of $\sim 13°$ for the outer arms and slightly smaller values for the inner arms. The data have also enabled the derivation of a new azimuthally averaged Milky Way rotation curve. The new curve is obtained by fitting the astrometric measurements to a model of the Galaxy. Unlike previous derivations that utilized only (1-D) radial velocities, it takes advantage of the newly measured 3-D motions and the new "gold standard" distances (e.g., Reid et al. 2012).

The analysis by Reid and collaborators has led to a new, accurate distance to the Galactic Center $R_0 = 8.38 \pm 0.18$ kpc and a circular rotation speed for the Sun of $\Theta_0 = 243 \pm 7$ km s^{-1}. These results clearly indicate the need for a revision in the International Astronomical Union (IAU) recommended values for these parameters.

10. WHITE DWARF BINARIES

J. Sokoloski reviewed the properties of accreting white dwarf binaries including cataclysmic variables (CVs) and symbiotic systems. In both types of binary, the main source of radio emission is outflows (collimated, uncollimated, and/or eruptive) which give rise to thermal bremsstrahlung and synchrotron emission from particles accelerated in shocks. Sokoloski pointed out that the recent confirmation of jets in CVs implies that all classes of accreting WD binaries are now known to have jets, although presently, only a handful of CV jets are known. In the case of symbiotics, >5% show evidence for collimated outflows, but the true fraction may be much higher, as the jets are transient, and to date, only a small fraction of such systems have been observed in a manner that would have permitted identification of the presence of a jet (e.g., via high resolution radio imaging) . One puzzle is why the jet fraction in CVs appears to be so much smaller than in symbiotics; explanations may include the larger accretion disks or larger accretion rates of symbiotics. Regardless, Sokoloski noted that the fact that jets are seen in different classes of WD binaries under a wide range of situations (e.g., various binary separations, different classes of donor stars; with or without shell burning) implies that the mechanism for jet formation must be quite robust. Sokoloski also noted that in some cases, evidence for a link between behavior in the disk and the jet has now been confirmed (similar to what is seen in X-ray binaries).

10.1. *Novae*

Accreting WD binaries produce the most common type of stellar explosion in the universe: novae. As described by J. Sokoloski, observations of novae in the radio are key to understanding the physics of these objects and in particular, to obtaining more accurate estimates of the mass of their ejecta. Indeed, one of the outstanding puzzles concerning classical novae is an order of magnitude discrepancy between the amount of material ejected by these explosions as inferred through observations compared with the amount predicted by theory. Since the ejecta mass is tied to all of the fundamental properties of the explosion as well as the evolution of the white dwarf, resolution of this discrepancy is deemed of critical importance. Sokoloski stressed that the ejecta masses derived from observations depend on a variety of assumptions (e.g., inherent sphericity; the shape of the density profile; a "Hubble flow" velocity profile; a fixed electron temperature), but that vastly improved constraints on these quantities are now becoming possible thanks to multi-frequency imaging observations of novae using the JVLA, including work by the EVLA Nova (eNova) project led by Sokoloski.

Sokoloski described how recent work by the eNova project has also led to some surprises. In the current standard picture, the radio emission from a nova is initially optically thick at all radio frequencies, and the radio flux increases with time as the optically thick ejecta grows in size. Once the growing ball of gas gets large enough, its density then drops sufficiently for it to become optically thin at higher frequencies, leading to a downturn in the radio light curve at successively lower frequencies. By monitoring the light curve at a wide range of radio frequencies over time, it is thus possible to probe the entire temperature and density structure of the remnant and derive a mass estimate, in a manner that can be equated to "peeling an onion". However, the simple picture of a homogeneously expanding shell of ionized gas (the so-called Hubble flow model) breaks down for two novae recently observed with the JVLA.

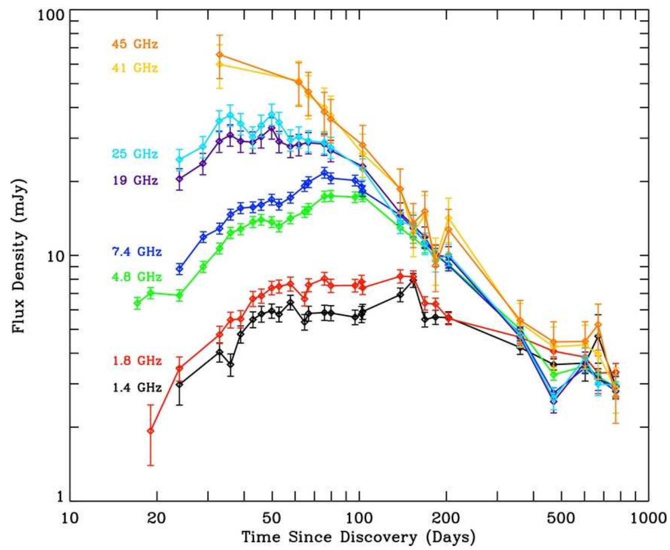

FIG. 7.— Multi-frequency radio light curve for nova V407 Cyg derived from JVLA measurements (Chomiuk et al. 2012a). The optical discovery of the nova occurred on 2010 March 10.8. Reproduced by persmission of the AAS.

In the case of V1723 Aql, recent JVLA light curves by Sokoloski and collaborators unexpectedly revealed a strong deviation from model predictions, suggesting the presence of a large quantity of optically thin material outside of the optically thick fireball (Krauss et al. 2011). Also, in the archetype of recurrent novae, T Pyx, the radio emission associated with a recent outburst was observed to be delayed by more than 50 days from the initial outburst, indicating a multi-stage ejection in which the bulk of the mass ($> 4\times10^{-5}\ M_{\odot}$—an order of magnitude higher than theoretical predictions) was delayed beyond the initial eruption (Nelson et al. 2012).

One particularly surprising development in the area of nova research came in 2010 with the discovery of γ-ray emission from the classical nova V407 Cyg. As related by M. Rupen (National Radio Astronomy Observatory), two additional γ-ray novae were detected during 2012. Our understanding of this phenomenon is still in its infancy, but as described by Rupen, radio observations are providing some key insights and serve as a crucial complement to optical and X-ray measurements.

V407 Cyg is a symbiotic binary, and JVLA observations of its nova outburst by Rupen and colleagues (Chomiuk et al. 2012a) revealed that the radio flux does not rise as steeply with time as predicted and is inconsistent with an optically thick thermal source (Figure 7). This can be explained if the radio emission is dominated not by the nova ejecta, but by a thermal component produced as the nova blast ionizes the red giant's wind. This is the first ever case where the radio light curve of a nova has been seen to be dominated by this mechanism. As detailed by Rupen, observations with MERLIN from days 11-20 following the outburst (Mioduszewski et al., in preparation) revealed a further surprise: material extended on scales of more than 1000 AU. Shocks/ejecta are unable to explain material at these distances over such short timescales, implying this must be pre-existing circumbinary material that has been flash-ionized. JVLA observations one year later subsequently showed two components (one thermal, one synchrotron) corresponding in position to the emission seen with MERLIN. This is interpreted as new material colliding with the large-scale material previously revealed by the MERLIN data.

As described by S. Deguchi, V407 Cyg has another unique trait in being the first classic nova found to have associated SiO maser emission (Deguchi et al. 2011). Subsequent monitoring of the SiO masers with Nobeyama showed that the SiO maser disappeared about 20 days after the nova eruption but then unexpectedly reappeared. This is interpreted as evidence that the emitting regions were destroyed by the nova shock (traveling at a speed of $\sim$3000 km s^{-1}), then later replenished.

Rupen explained that for V407 Cyg, it was initially suspected that interaction between the nova ejecta and the dense wind of the red giant primary (i.e., shocks) was responsible for the production of its γ-ray emission. However, the subsequent detection of γ-rays from Nova Sco 2012 and Nova Mon 2012, neither of which is known to have a similarly dense medium present, seems to rule out this explanation. Additionally, in the case of Nova Sco 2012, a link with strong shocks appears to be excluded by the lack of X-ray emission. So far a common thread that can explain the production of γ-rays in these three novae remains elusive. All three have been subsequently detected in the radio, indicating significant mass outflow, and future radio observations are expected to help better quantify this.

11. SUPERNOVA PROGENITORS

Despite decades of research, the progenitor stars associated with the various subclasses of supernovae remain poorly known. However, as described in the review talk by L. Chomiuk (National Radio Astronomy Observatory/Michigan State University), a wealth of important new insights has been emerging from radio wavelength studies.

The radio emission from supernovae arises from synchrotron radiation produced by the interaction between the supernova shock wave and the pre-existing circumstellar material. As this shock wave propagates through the CSE, it effectively samples the density of the local environment as a function of distance from the star. Thus by studying the radio light curves of supernovae, we can probe the mass loss history of the progenitor and hence glean important clues as to its nature. As described by Chomiuk, the radio light curves accumulated over the past four decades point to a diverse range of mass-loss histories.

Chomiuk reminded us that radio emission (or lack thereof) was fundamental to the recognition of a distinction between Type Ia and Type Ib/c supernovae. Furthermore, despite numerous efforts, no Type Ia supernova has yet to be detected in the radio. Some of the most recent attempts were made by Chomiuk and collaborators as part of a program aimed at searching for radio emission from every Type Ia supernova within 30 Mpc and accessible to the JVLA. The absence of radio emission from this class of supernovae argues against symbiotic progenitor systems (in which a white dwarf is accreting material from a red giant donor) since their dense environments should produce detectable levels of radio emission (Chomiuk et al. 2012b).

SN1970G was the first supernova ever detected at radio wavelengths and posed a significant challenge to the radio instruments of its day (e.g., Gottesman et al. 1972). Chomiuk reported that in 2011, it became the supernova with the longest ever recorded light curve (more than 40 years) when it was detected with the JVLA at a flux density of a mere 33.7$\pm$4.3μJy at 5 GHz (Dittman et al., in preparation).

A new insight type IIn supernovae came in July/August 2012 when observers were able to watch a luminous blue variable (LBV) and former "impostor" supernova SN2009ip explode as a bona fide supernova. This is the first time that a type IIn supernova has been definitively linked with an LBV. It also represents the first time that we have information on the mass loss history of a star and a historical light curve prior to its explosion. This will thus serve an important test case for the interpretation of mass-loss histories inferred from subsequent radio observations. Chomiuk reported that JVLA monitoring of SN2009ip is ongoing but that no radio counterpart had been detected as of the time of the workshop. This is not unexpected given that type IIn supernovae are typically associated with dense environments where free-free absorption can impede the radio emission from rising to the level of detectability for several months following the explosion.

R. Ignace (East Tennessee State University) presented new ideas on how Faraday rotation measurements could be used as a probe of stellar wind bubbles (and supernova shells), potentially providing clues on the nature of the central star and its wind as well as stellar magnetic fields (Ignace & Pingel 2013). He presented analytic models of wind cavities threaded by magnetic fields of different geometries (azimuthal or split monopole) and the characteristic signatures that they would impart on the observed position angle rotation (or rotation measure) maps. He concluded that only the azimuthal field is likely to lead to detectable Faraday rotation signals. In this case, a characteristic antisymmetry (sign flip) is predicted in the rotation measure map that is completely independent of the viewing inclination. Using an azimuthal field model, he showed that the resulting position angle map reproduces the main features seen in observations of the supernova remnant G296.5+10.0.

Ignace also proposed the novel possibility of studying variable Faraday rotation from the evolving ionization front of a supernova as a means to studying the magnetic field in the ISM. In this case, the interstellar field will be static, but as the ionized bubble grows, different field scale lengths will be sampled. Such studies may soon be within the realm of possibility within very nearby galaxies using VLBI techniques.

12. CLOSING DISCUSSION

The final scientific talk of the Radio Stars workshop was an overview and perspectives talk presented by S. Kwok. Several highlights from this presentation are described in the relevant sections above. The workshop then concluded with an open discussion moderated by T. Bastian. This discussion comprised in large part musings and prognostications about the future of radio science in general rather than problems unique to the stellar community.

A concern voiced by several participants related to the growth of data volumes at rates that have already begun to challenge or exceed astronomers' ability to handle them. It was noted, for example, that by 2013, the JVLA will already be producing more than a petabyte per year. The problem becomes particularly severe for dynamic imaging spectroscopy (see also §6.5), where the time, space, frequency, and polarization information effectively produce a 5-D data set, and it was questioned whether computing and software tools will be able to keep pace with growing needs. Confronting this issue was deemed vital to insuring maximum scientific return on our investments in new instrumentation.

It was recognized that scientists may have to approach modern radio data with the intent of asking very specific questions (e.g., characterization of a particular spectral feature) and that it will become impossible to take advantage of the entire information content of most data sets. Similarly, traditional approaches to interferometric data analysis will likely need to evolve to methods that address specialized needs (e.g., fitting models directly to the *u*-*v* data rather than producing large maps). A downside noted to this approach is the possibility that science will become less curiosity-driven and less open to the kind of serendipity that is often so crucial to driving scientific progress. Such fears seem to be reinforced by the reality of competing for limited research funding, with pressure felt to pursue research topics deemed high priority by funding agencies and having well-defined outcomes.

There was a consensus that given the rich, multi-dimensional nature of the data sets expected from current and planned radio facilities, essentially all data sets will effectively be "legacy" data with the potential to be mined for future science well beyond the goals or needs of the original proposal. For this reason, archiving data from new instruments, processed in a uniform and systematic way and without loss of information, was seen to be critical.

It was pointed out that a sensitive all-sky radio survey could be a tremendous resource for the community and a valuable complement to counterparts planned at optical and other wavelengths. However, it was anticipated that resources to carry out such a survey are unlikely to be forthcoming in the near term. Lastly, given the well-recognized power of multi-wavelength science, another concern that was voiced was the multiple jeopardy incurred when attempting to secure observing time on multiple highly oversubscribed instruments along with subsequent funding support to carry out the analysis.

While no simple or clear-cut solutions to most of the above issues emerged from the Radio Stars workshop, it is hoped that the discussions stimulated some new thinking that will eventually help to lead to constructive solutions to these complex issues.

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