6q. Radio Astronomy

EUGENE E. EPSTEIN

The Aerospace Corporation

Radio astronomy involves the study of that emission from astronomical objects that falls in the radio portion of the electromagnetic spectrum [arbitrarily defined here as the range from 1 mm (300 GHz) to 1 km (300 kHz)]. Because of absorption by the earth's ionosphere, observations at $\lesssim 10$ MHz are usually made by spaceborne equipment. At $\gtrsim 20$ GHz, absorption by molecular constituents in the earth's atmosphere (principally water and oxygen) becomes increasingly severe with frequency; however, valuable observations at 220 GHz can still be made at sea level [1]. Large radio telescopes achieve resolutions of the order of 2 arc minutes; however, interferometers and arrays can achieve much finer resolution. Intercontinental interferometers have recently achieved the equivalent of 0.001 arc second resolution [2].

The basic quantity measured by radio astronomers is flux S defined as

$$S = \iint B(\theta,\phi)\, d\Omega$$

where B is the brightness as a function of position on the sky, in $W/(m^2 \cdot Hz \cdot sr)$. For convenience, radio astronomers often equate B with the Planck blackbody radiation function; hence, signal strengths are frequently expressed in terms of the brightness temperature of an equivalent blackbody. Since $h\nu \ll kT$ for most, but not all, radio astronomical cases of interest, the Rayleigh-Jeans approximation to the Planck function is often used;[1] it is,

$$B = \frac{2h\nu^3}{c^2}\frac{kT}{h\nu} \approx \frac{2kT}{\lambda^2}$$

Typical fluxes of astronomical objects range from 10^4 to 10^{-3} flux units [1 flux unit = 10^{-26} W/(m$^2 \cdot$ Hz)]. Flux densities at 400 MHz and spectra of a number of representative radio sources are given in Table 6q-1 and Fig. 6q-1, respectively.

TABLE 6q-1. FLUX DENSITIES OF SOME NONTHERMAL RADIO SOURCES*

Source	*Flux density at* 400 *MHz*†
Cassiopeia A	6,100
Cygnus A	4,500
Hydra A	133
Taurus A	1,230
Virgo A	580
3C 28	66
3C 48	36
3C 98	25
3C 147	52
3C 273	59
3C 286	23
3C 295	52
3C 298	24
3C 310	25
3C 452	29
CTA 21	9
CTA 102	6

* Adapted from J. D. Kraus, "Radio Astronomy," McGraw-Hill Book Company, New York, 1966.
† In flux units [10^{-26} W/(m$^2 \cdot$ Hz)].

Sources of radio emission can be considered in three broad categories: solar system objects, galactic objects, and extragalactic objects. A brief overview follows; most of the references cited here are review articles.

6q-1. Solar System Objects. Solar radio emission can be described as originating from both a "quiet Sun" and an "active Sun" [3]. The active Sun emission is time-varying on a scale ranging from fractions of a second at wavelengths in the decameter range to minutes, hours, or days at shorter wavelengths. This short-term activity frequently originates in the solar corona and is often closely associated with optically observed sunspot and flare activity. The quiet Sun emission, as the appellation implies, is not generally associated with variable phenomena of the Sun, except the 11-year solar cycle.

Radio emission from the Moon [4,6], Mercury [5,6], and Mars [6] (objects with little or no atmosphere) arises from their surface layers and reveals information about the thermal and electrical properties of these layers. Emission from Venus [6,7], Jupiter [6], Saturn [6], Uranus [6], and Neptune [6] provides information on the thermal properties of their atmospheres and important constraints on models of their atmospheres. Observations of Jupiter [8] have also revealed the presence of an extensive magnetosphere filled with charged particles in a fashion similar to the Earth's Van

[1] For a more complete discussion of radiation measurements, see J. D. Kraus, "Radio Astronomy," McGraw-Hill Book Company, New York, 1966. This is an excellent general treatise on the subject and includes a historical introduction and thorough discussions of antennas and receivers. Another important reference is A. D. Kuz'min and A. E. Salomonovich, "Radioastronomical Methods of Antenna Measurements," translated by E. Jacobs, Academic Press, Inc., New York, 1966. Also, for a general handbook on astronomy, see C. W. Allen, "Astrophysical Quantities," The Athlone Press, University of London, 1963.

Allen belts. Radar studies [6,7,9] of the Moon and planets have yielded information on surface roughness, dielectric constants, topographic features, orientations of rotation axes, and rotation rates (revealing, for example, that Venus is in retrograde rotation with a period of 243 days).

6q-2. Galactic Objects. The broad patterns of the spiral structure of our galaxy have been traced out by radio spectroscopic studies of the 21-cm (1,420-MHz) emission line of neutral hydrogen (HI) gas [10]. The Doppler shifts and angular distributions of the line emission give information on galactic dynamics. The line intensities give information on the densities of the HI gas concentrations. Studies

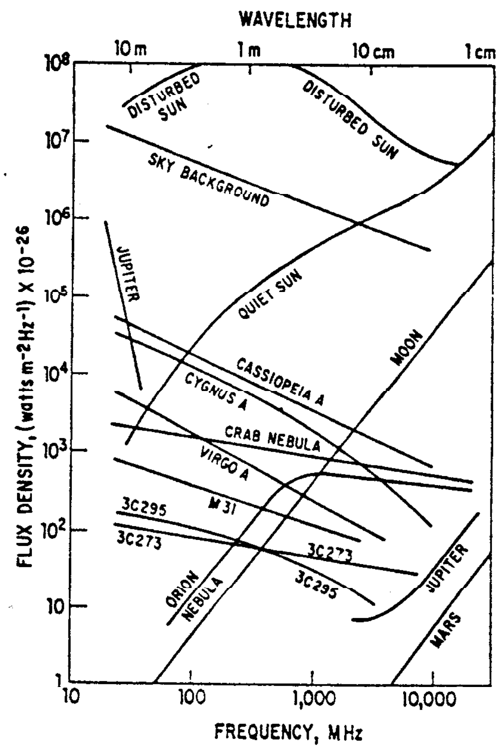

FIG. 6q-1. Spectra of typical radio sources. [*From J. D. Kraus, "Radio Astronomy," McGraw-Hill Book Company, New York,* 1966.]

of continuum [11] radiation reveal the concentration of emission to the galactic plane and to the galactic center (just as the 21-cm line studies do). The continuum radiation is of two kinds: thermal emission (also known as free-free emission and as coulomb bremsstrahlung) from regions of ionized hydrogen (HII) gas and synchrotron radiation (also known as magnetobremsstrahlung) from electrons with relativistic velocities moving in weak magnetic fields [12].

Thermal emission data have led to the identification of many dense HII regions. These regions also emit recombination lines [13] ($n \rightarrow n - 1$ transitions, where $n \sim 50$ to ~ 150). Also found originating near these regions are 18-cm lines from OH radicals [14] that are often highly polarized and variable in intensity. The emission regions are usually quite small (a fraction of an arc second), and the emission intensity occasionally corresponds to brightness temperatures as high as 10^9 K! Such high brightness temperatures are clearly not thermal in origin, and "masering" action has been proposed as the explanation, with pumping resulting from intense UV or IR radiation coming from stars embedded in the same cloud.

Emission lines from NH_3 (1.25 cm, 24.0 GHz), H_2O (1.35 cm, 22.2 GHz), and CH_2O (6.21 cm, 4.83 GHz) have recently been detected[1] from these regions of dense gas; in some cases, the H_2O may be "masering." This kind of observation provides data on the structure and dynamics of these regions and, with varieties of other data, has pointed to the suggestion that star and planetary formation is occurring in these regions. With C, H, N, and O, all the ingredients for life are present. It has been further suggested that perhaps life originated not in the primordial oceans on the surfaces of planets, but rather in the primordial clouds out of which the stars and planetary systems condensed.

A recently discovered category of galactic objects of great interest is pulsars.[2] The radio emission from these objects is pulsed in character, with interpulse periods ranging from 30 msec to 4 sec. In a few cases, the interpulse periods have been found to be slowly lengthening. The pulse amplitudes are not constant. Pulsars are thought to be rapidly rotating neutron stars, which are the remnants of supernovae. However, the exact mechanism of radiation is unknown.

6q-3. Extragalactic Objects. HI line emission at 21 cm has been detected from many nearby galaxies [15]. Continued emission has also been detected at many wavelengths from normal galaxies; the radio power output is of the order of 10^{30} to 10^{32} W. There are also many *radio* galaxies, so called because their radio power output is much higher—of the order of 10^{35} to 10^{38} W (see Table 6q-2.) Other strong emitters of radio (and optical) energy are the quasi-stellar radio sources [16] (abbreviated as either quasar, QSO, or QSS)—10^{37} to 10^{38} W. QSS are the most rapidly moving and most distant objects of which we are aware—velocities up to ≈ 0.8 c, and distances up to a few billion light years. One school of thought holds them to be galaxies in very early stages of formation when nonequilibrium conditions obtain. Their angular sizes seem to be a function of radio wavelength, being as small as $\sim 10^{-3}$ arc seconds for some objects [2] at $\lambda \approx 10$ cm. Many radio sources are variable in flux [17] (see Fig. 6q-2), and in some sources repeated outbursts have been measured [18]. The sequence of events depicted in Fig. 6q-2 is thought to be the result of an adiabatically expanding cloud of relativistic electrons in a weak magnetic field (10^{-3} to 10^{-5} gauss); however, the origin of the relativistic electrons is unknown. Seyfert galaxies [19] constitute a class of objects thought to be an intermediate evolutionary stage between QSS and normal galaxies because some of their radio characteristics (spectra and time

TABLE 6q-2. POWER OUTPUT OF ASTRONOMICAL OBJECTS

Object	Optical power, watts	Radio power, watts
White dwarf star	10^{23}	?
Sun	4×10^{26}	10^{12}
Supergiant star	10^{31}	?
Flare star	10^{25}	10^{16}
Supernova remnant	10^{29}	10^{28}
Normal galaxy (10^{11} solar masses)	10^{37}	10^{30}–10^{32}
Radio galaxy	10^{37}	10^{35}–10^{38}
Quasi-stellar radio source	10^{39}	10^{37}–10^{38}

From J. D. Kraus, "Radio Astronomy," McGraw-Hill Book Company, New York, 1966.

[1] See the current literature for information on this new and rapidly growing area of radio astronomy.

[2] The current literature contains information on this exciting new field.

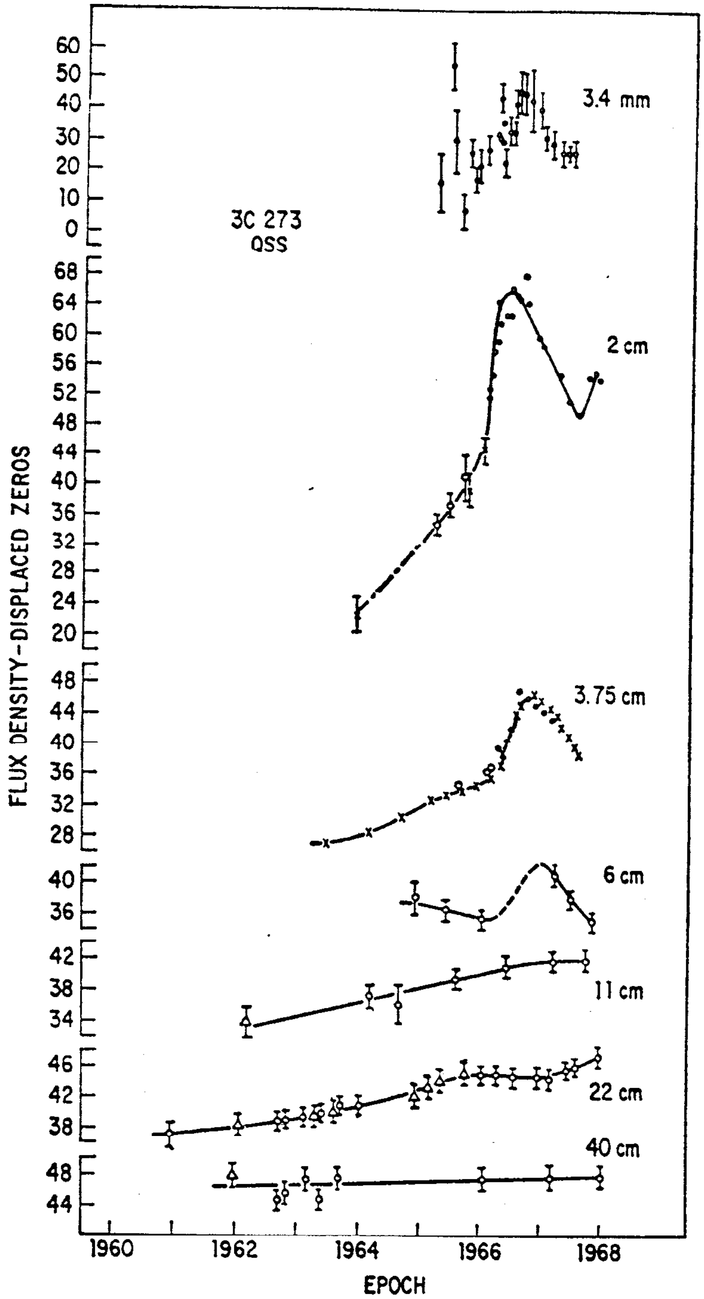

Fig. 6q-2. Variations with time of the flux at several wavelengths from the quasi-stellar radio source 3C273. [*From K. I. Kellermann and I. I. K. Pauliny-Toth, Ann, Rev. Astron. & Astrophys.* **6**, 417 (1968).]

variability) and optical characteristics (excited, turbulent nuclei) resemble those of QSS; yet, in general appearance, they resemble more-or-less normal galaxies. Extensive statistical analyses, important in cosmological studies [20], have been made of the numbers of radio sources as a function of flux [21].

Another feature of the radio sky that has contributed to cosmological investigations is the microwave background [22]. This radiation, corresponding to that from a 2.7 K blackbody, is postulated to be the much diluted radiation left over from the fireball that occurred at the time of the origin of the Universe. It is apparently isotropic to a high degree, and has been observed at wavelengths from 3 mm to 20 cm.

References

1. Reber, E. E., and J. Stacey: 3.4- and 1.4-mm Observations of the Lunar Eclipse on 18 October 1967, *Icarus* **10**, 171 (1969).
2. Cohen, M. H., D. L. Jauncey, K. I. Kellermann, and B. G. Clark: Radio Interferometry at One-thousandth Second of Arc, *Science* **162**, 88 (1968).
3. Kundu, Mukul R.: "Solar Radio Astronomy," Interscience Publishers, Inc., New York, 1965; Jules Aarons, ed.: "Solar System Radio Astronomy," Plenum Press, Plenum Publishing Corporation, New York, 1965.
4. Weaver, H.: The Interpretation of Thermal Emission from the Moon, "Solar System Radio Astronomy," Plenum Press, Plenum Publishing Corporation, New York, 1965.
5. Morrison, David, and Carl Sargan: The Microwave Phase Effect of Mercury, *Astrophys. J.* **150**, 1105 (1967); also, David Morrison: On the Interpretation of Mercury Observations at Wavelengths of 3.4 and 19 mm, *ibid.* **152**, 661, 1968.
6. Proceedings of the 1969 IAU-URSI Symposium on Planetary Atmospheres and Surfaces, *Radio Sci.*, Vol. 5 (February, 1970); also, Proceedings of the 1965 IAU-URSI Symposium on Planetary Atmospheres and Surfaces, *Radio Science* **69D**, (December, 1965).
7. The Atmosphere of Venus, Proceedings of the Second Arizona Conference on Planetary Atmospheres, *J. Atmospheric Sci.* **25**, (July, 1968).
8. Smith, Alex G.: Jupiter, The Radio-active Planet, *Am. Scientist* **57**, 177 (1969); also, James W. Warwick: Radio Emission from Jupiter, *Ann. Rev. Astron. & Astrophys.* **2**, 1 (1964).
9. Evans, John, and Tor Hagfors: "Radar Astronomy," McGraw-Hill Book Company, New York, 1968; also, Gordon H. Pettengill and Irwin I. Shapiro: Radar Astronomy, *Ann. Rev. Astron. & Astrophys.* **3**, 377 (1965).
10. Bok, Bart J.: The Spiral Structure of Our Galaxy, *Am. Scientist* **55**, 375 (1967).
11. Mills, B. Y.: Northermal Radio Frequency Radiation from the Galaxy, *Ann. Rev. of Astron. & Astrophys.* **2**, 185 (1964).
12. Ginzburg, V. L., and S. I. Syrovatskii: Cosmic Magnetobremsstrahlung, *Ann. Rev. Astron. & Astrophys.* **3**, 297 (1965).
13. Mezger, P. G., and Patrick Palmer: Radio Recombination Lines: A New Observational Tool in Astrophysics, *Science*, **160**, 29 (1968).
14. Barrett, Alan H.: Radio Observations of Interstellar Hydroxyl Radicals, *Science* **157**, 881, 1967; also, B. J. Robinson and R. X. McGee: OH Molecules in the Interstellar Medium, *Ann. Rev. Astron. Astrophys.* **5**, 183 (1967).
15. Roberts, Morton S.: Neutral Atomic Hydrogen in 32 Galaxies of Small Angular Diameter, *Astron. J.* **73**, 945 (1968).
16. Burbidge, E. Margaret: Quasi-stellar Objects, *Ann. Rev. Astron. & Astrophys.* **5**, 399 (1967); G. R. Burbidge and E. M. Burbidge: "Quasi-stellar Objects," W. H. Freeman and Company, San Francisco, 1967.
17. Kellermann, K. I., and I. I. K. Pauliny-Toth: Variable Radio Sources, *Ann. Rev. Astron. & Astrophys.* **6**, 417 (1968).
18. Pauliny-Toth, I. I. K., and K. I. Kellermann: Repeated Outbursts in the Radio Galaxy 3C 120, *Astrophys. J.* **152**, L169 (1968).
19. Proceedings of the Conference on Seyfert Galaxies and Related Objects, *Astron. J.* **73**, 836 (November, 1968); Ray J. Weymann: Seyfert Galaxies, *Sci. Am.* **220**, 28 (1968).
20. Novikov, I. D., and Ya. B. Zeldovic: Cosmology, *Ann. Rev. Astron. & Astrophys.* **5**, 627 (1967); Allan Sandage: Observational Cosmology, *Observatory* **88**, 91 (1968).
21. Ryle, M.: The Counts of Radio Sources, *Ann. Rev. Astron. & Astrophys.* **6**, 249 (1968).
22. Partridge, R. B.: The Primeval Fireball Today, *Am. Scientist* **57**, 37 (1969).