Observational Aspects of Cosmology

Quasi-stellar objects ("quasars") were the prime topic of discussion among 100 or more astronomers and physicists in conference at Miami, Florida, 15–17 December 1965, who heard 40 invited speakers present new data and calculations obtained since last year's conference in Austin, Texas. Three major problems emerged: (i) how to distinguish between truly distant extragalactic objects and nearby stellar objects; (ii) physical models that explain the observed properties of quasars; and (iii) cosmological theories consistent with the new observations. Present were optical astronomers, radio astronomers, and theoretical physicists, primarily from American universities and observatories, but with a few from England, France, and Australia. The program was organized by R. Minkowski, F. Haddock, A. Cameron, R. Dicke, and E. Schucking; S. F. Singer (Miami University) was host with the support of NSF, NASA, and ONR.

Identification of Quasi-Stellar Objects

The class of quasars resulted from identification of optical images near the positions of small radio sources in the sky and from the discovery that many of the small ones have large redshifts, up to $z = \Delta\lambda/\lambda = 2$, and no proper motions. Allan Sandage (Mount Wilson) reported on efforts to identify many more of these extragalactic quasars by their characteristic blue color by use of the Palomar-Haro-Luyten (PHL) catalog of 8700 blue stars in some 1700 square degrees of the sky near the southern galactic pole. At first he thought that more than 50 percent of the 8000 fainter than 16^{m} (magnitude 16) were extragalactic, some of them radio-quiet. Tom Kinman (Lick) obtained spectra of 24 of these PHL objects, one of which was a radio-quiet galaxy with $z = 1.93$. However, he considers that half of them are white dwarfs and that another 30 percent are halo stars near our galaxy, leaving 20 percent as possible extragalactic objects. Luyten (Minnesota) noted that these estimates imply a very large number of white dwarf stars—more than 80,000 brighter than 18.9^{m}.

Sandage and Kinman summarized the observed characteristics of the extragalactic objects as follows: (i) 52 radio sources are definitely identified with 35 optical galaxies and 17 quasars, all with measured redshifts and magnitudes; (ii) 65 others are identified with optical objects at the same position in the sky; (iii) 77 others are near optical objects; therefore a total of 192 are probably so identified among some 10,000 in the new "4C" Cambridge catalog (see Table 1, which is incomplete).

Average absolute magnitudes are -24.7 visual (-26 photographic) for quasars and -21.6 visual for the most luminous cluster galaxies (0.06 as bright). Variability of quasars is of two types: sudden variations larger in the ultraviolet than in the visual, and slower variations (over 10 years or more) of about 1^{m}. There is little spread ($\pm 0.4^{m}$) in the absolute magnitudes of quasars, but the blue galaxies range from -17 to -21^{m} (photographic), the former being ten times more numerous [1 per 1000 cubic megaparsecs (Mp^3)]. Color is correlated not with redshift but with absolute magnitude; the brighter galaxies are bluer.

Sciama (Cambridge) interprets the large number of radio sources found in the fourth (4C) survey as a mixture of two types: highly luminous extragalactic (e) objects distributed uniformly, and faint galactic (g) objects. The relative numbers, $N_0(S)$, of radio sources brighter than flux density S, increase as S is decreased from several hundred flux units [1 fu $= 10^{-26}$ watt m^{-2} cps^{-1} (cycles per second)]. A plot of log N_0 versus log S shows a changing slope, starting at -1.5, steepening to -1.8 for S between 17 and 0.5 fu, and flattening to -1.3 for S between 0.5 and 0.25 fu (the limit of the 4C survey at 178 Mc/sec) (see Fig. 1). P. Veron (Meudon) considers that these counts reflect changes in the numbers of quasars during the history of the universe, but Sciama has an alternative explanation.

If radio sources were all of the same intrinsic luminosity (P watt/cps) and distributed uniformly throughout transparent space on all sides of us, one would expect $S = 10^{26}P/4\pi D^2$ and $N = 4\pi\rho D^3/3 = 10^{38}\rho(P/S)^{3/2}$, or a slope of -1.5 on the plot of log N versus log S. Since most of the bright radio sources have been identified with optical galaxies, D can be calculated from Hubble's law: $D = V/H = 10^{26}z$ (in meters, for small z); and P can be calculated from S and D. The median value is $P_e = 4 \times 10^{26}$ watt/cps at 178 Mc/sec, yielding a density, ρ_e, of 1.5 $\times 10^{-74}$ m^{-3}, or $4 \times 10^{-7}/Mp^3$—one radio galaxy per 2.5×10^{6} Mp^3, or 1/400th as numerous as blue galaxies of absolute photographic magnitude -17, with $\rho = 10^{-3}/Mp^3$, found by Kinman.

Assuming ρ_e to be constant and a spread of a factor of 10 in P_e, Sciama computed the expected $N_e(S)$, corrected for the effect of redshift on S, that flattens the slope to -1.2 on the logarithmic plot; he then used the difference $N_0 - N_e = N_g$ as the number of galactic objects assumed to lie within 400 p (parsecs) of the plane of our galaxy. The intrinsic luminosity P_g, 4×10^{11} watt/cps at 178 Mc/sec, was adjusted to fit the observed sky background near the galactic poles; the density ρ_g was then found to be $10^{-2}/p^3$, decreasing slowly with $D^{-0.15}$ for $20 < D < 400$ p. There is a gap with $\rho_g = 0$ for $D < 20$ p from Sun, and an asymmetry is expected for $D > 400$ p, corresponding to $S < 0.1$ fu. This asymmetry, proper motions, and the predicted $N_0 = N_e + N_g = 44{,}000$ radio sources brighter than $S = 0.1$ fu remain to be checked by radio observations at 178 Mc/sec.

In summary, five types of objects have been identified that were previously confused with one another: radio galaxies, a small fraction of the optical galaxies with extended images; galactic radio sources with no optical images yet detected; blue galaxies with small optical images, large redshifts, and no radio emission as yet detected; and quasistellar radio sources, which have small optical images and large redshifts. Only the last two types are properly termed quasars.

Physical Models of Quasi-Stellar Objects

Observations of optical spectra, radio spectra, luminosity (both optical and radio), polarization, and angular dimensions provide a basis for a variety of theoretical models of quasars proposed or discussed by a dozen speakers. Optical spectra were first described by Maarten Schmidt (Caltech) and Margaret Burbidge (San Diego), who summarized observations of 34 quasars, 23 of them showing several lines each, yielding reliable values of redshift, z, between 0.158 and 2.1. The spectra of eight others show only one line each, and three others (3C93, 3C186, 3C196) show no lines. The high-excitation, "forbidden," emission lines characteristic of low-density gaseous nebulae near hot stars are often seen, often quite broad and strong. Redshifts $\geqq 1.6$ permit observations of the ultraviolet down to $\leqq 1200$-Å wavelengths, unshifted, including: H, $\lambda 1216$ (Lyman-alpha); C IV, $\lambda 1550$; He II, $\lambda 1640$; C III, $\lambda 1909$; C II, $\lambda 2512$; Mg II, $\lambda 2798$; Ar IV, $\lambda 2869$ (forbidden); He II, $\lambda 3203$; Ne V, $\lambda\lambda 3346$, 3426 (forbidden); O II, $\lambda 3727$ (forbidden); and O III, $\lambda\lambda 5001$, 4959 (forbidden).

In the spectrum of a radio-quiet, small, blue galaxy, Kinman observed $\lambda\lambda 1216$ and 1550; also: O IV, $\lambda 1406$; Ne V, $\lambda 1575$ (forbidden); and Ne IV, $\lambda 1602$ (forbidden). The last two, and a possible detection of $\lambda 1206$ (Lyman-beta) in 3C9 by Wampler, are doubtful. Margaret Burbidge found a variable redshift in 3C345, with an amplitude of 700 km/sec. E. J. Wampler (Lick) found the profile of Mg II $\lambda 2798$ variable; also variability of the continuum in 3C345. Both he and Mrs. Burbidge found partial absorption at wavelengths just short of Lyman-alpha—possible evidence of absorption by intergalactic hydrogen with somewhat smaller redshift (see Fig. 4).

K. I. Kellerman (NRAO) summarized observations of radio spectra for about 1000 radio sources over the frequency range $26 < f < 8000$ Mc/sec, most of them between 38 and 3000 Mc/sec ($790 > \lambda > 10$ cm). These are usually simple "power-law" spectra, with S proportional to f^{α} where the mean value is $\bar{\alpha} = -0.77$ and $-1.3 < \alpha < -0.25$, although the slope α on a log S versus log f plot is steeper for $f > 1400$ Mcy sec^{-1} ($\lambda < 21$ cm). There is no correlation between the value of α and either the apparent radio brightness S or the intrinsic radio power of the source P in the ranges $S > 2.6$ fu and $10^{31} < P < 10^{38}$ watt/cps at $f = 178$ Mc/sec. However, α is less steep for compact radio sources of small angular diameter, and the log S versus log f plot is curved in 5 to 10 percent of the sources; most of these "curved spectra" are of quasars (see Fig. 5).

Curved spectra having maxima in S near $f = 30$ Mc/sec ($\lambda = 10$ m) result from synchrotron self-absorption; the object must have high surface brightness, and the radio-emitting relativistic plasma must be less than 10 p in diameter. Since synchrotron radiation losses tend to steepen the spectrum at the high-frequency end, Kellerman assumed that the flattest spectra with $\alpha = \alpha_1 \approx -0.25$ are from recently formed radio sources, and showed that the "break" to steeper slope, $\alpha_2 \simeq -0.75$, occurs at frequency $f_b = 10^3/H^3t^2$. In many spectra this "break" occurs below $f = 10^4$ Mc/sec and, since age t must be less than 10^{10} years, this fact implies that the magnetic field H is about 10^{-7} gauss, and that f_b slowly decreases with time.

Table 1. Quasi-stellar objects. See *Astrophys. J.* **142**, 409, 1156, 1290, 1306, 1669 (1965); *Monthly Notices Roy. Astron. Soc.* **131**, 165 (1965). Abbreviations: UV, ultraviolet; S, radio flux at 178 Mc/sec; v, variable. Magnitudes from A. R. Sandage.

Name	Magnitude			Spectrum		S (fu)
	Visual	Blue	UV	Lines	z	
3C9	18.2	18.4	17.7	Lyman α, C IV	2.012	75
3C47	18.1	18.2	17.5		0.425	160
3C48	16.2	16.6	16.0	Mg II, O II, O III	0.368	45
3C93	18.1	18.4	17.9	None		
3C138	18.8	19.4	19.2			10
3C147	17.8	18.5	18.1		0.545	15
3C181	18.9	19.3	18.3			60
3C186	17.6	18.1	17.4	None		
3C190	17.5	17.3	16.4			65
3C191	18.4	18.7	17.8			
3C196	17.6	18.2	17.8	None		210
3C204	18.2	18.8	17.8			
3C207	18.2	18.6	18.2			40
3C208	17.4	17.8	16.8			90
3C215	18.3	18.5	17.8			
3C216	18.3	18.8	18.2			95
3C217	18.5	18.8	17.9			
3C245	17.3	17.7	16.9	C III, Mg II, Ar IV	1.029	45
3C247	18.8	19.3	19.1			25
3C249.1	15.7	15.7	14.9			
3C254	18.0	18.1	17.6	C III, Mg II,*	0.734	
3C261	18.2	18.5	17.9			
3C263	16.3	16.5	15.9			
3C268.2	18.3	18.7	18.5			
3C270.1	18.6	18.8	18.2			
3C273A, B	12.8v	13.0	12.2	Lyman α, Mg II	0.158	100v
3C275.1	19.0	19.2	18.8			
3C277.1	17.9	17.8	17.0			
3C279	17.8	18.0	17.4	Mg II, Ne V, O II, H	0.536	15v
3C280.1	19.4	19.3	18.6			30
3C281	17.0	17.2	16.6			
3C286	17.3	17.5	16.7	Mg II, Ne V, C III	0.846	25
3C287	17.7	18.3	17.6	C III, C IV, Mg II	1.055	
3C295					0.461	85
3C298	16.8	17.1	16.5			75
3C334	16.4	16.5	15.7	Mg II, O III, He II	0.555	
3C336	17.5	17.9	17.0			
3C343.3						
3C345		17v		Mg II, He II, Ne V	0.595v	15v
3C351				Ne V, O II, O III, H	0.371	
3C375						v
3C380				Mg II, Ar IV, Ne V	0.691	62
3C446	18.4	18.8	17.9		2.07	
CTA21						9
CTA102	17.3	17.7	16.9	C III, Mg II	1.038	7v
PHL256				H, He I	0.131	
PHL938				Lyman α, C IV, O IV	1.93	0
MSH14-121	17.5			Mg II, O III, Ne V	0.938	
0106+01	18.4	18.5	17.8	Lyman α, C IV, C III	2.107	1
0922+14	18.0	18.5	18.0			1
0957+00	17.6	18.0	17.3			1
1116+12	19.3	19.4	18.6			2
1217+02	16.5	16.6	15.7			1
1252+11	16.6	17.0	16.2	Mg II, Ar IV, O III	0.870	1

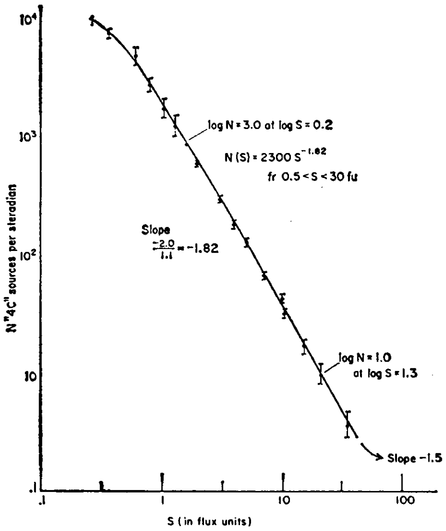

Fig. 1. Quasi-stellar objects: counts of radio sources. [Courtesy D. W. Sciama]

Alan Moffet (Caltech) looked for changes in S from 28 quasars, during a 4-year interval, at frequencies from 1000 to 10,000 Mc/sec. No variation was detected at the lower frequencies, but 11 of the sources proved variable at $f > 1400$ Mc/sec ($\lambda < 21$ cm); typical was 3C273, with $dS/dt = 1.7$ fu/year at 21 cm and 3.3 fu/year at 3.75 cm. W. A. Dent (Michigan) found three others with comparable variations in S—about 40 percent per year at $\lambda = 3.75$ cm, some increasing and some decreasing; he noted that these radio variables have flatter-than-average spectra at high frequencies—an indication of one or more small emission regions of high surface brightness.

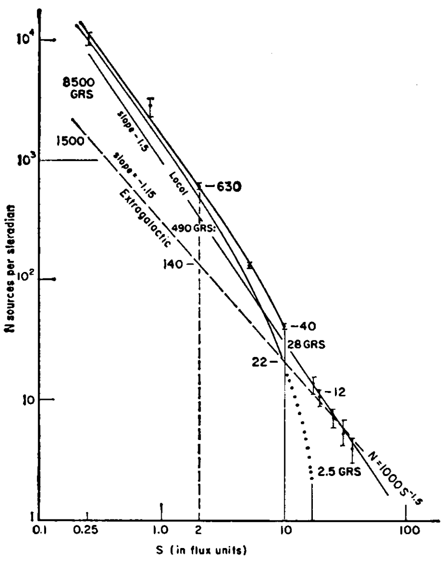

Fig. 2. Quasi-stellar objects: Sciama's interpretation of radio-source counts. *GRS*, galactic radio sources.

Moffet reported a theoretical model that explains these variations as resulting from repeated injection of high-energy (relativistic) electrons in numbers proportional to $1/(\text{energy})^3$. Plasma clouds, of diameter $A \simeq 10$ p and of intrinsic power $P \simeq 10^{33}$ watt/cps, will have synchrotron self-absorption at frequencies $f > 3000$ Mc/sec, and the cutoff frequency, f_c, will be given by $f_c^{2.5} = 2700\ SH^{1/2}\theta^{-2}$, where (the angular diameter in seconds of arc) $\theta = 206{,}265\ A/D$, D being the distance in parsecs. The synchrotron emission, S, is proportional to nH^2A^3/f_cD^2, and Moffet can match the observed values of S, θ, and dS/dt with $A = 4$ p, $H = 10^{-16}$ gauss, and total energy $= 10^{61.5}$ ergs.

The optical variations, as Sandage noted, divide into two types: (i) sudden variations within a week or so, for which the color changes, the amplitude being greater in the ultraviolet than in the yellow and red; (ii) slow variations, over periods of 10 years or so, which are larger, amounting to a factor of $\geqq 2$.

P. A. Sturroch (Stanford) based his explanation on giant flares in the radio source. If these are like solar flares, a mass of plasma is supported against gravitation by a twisted magnetic field, H, that is assumed to be intensified during a previous contraction of the plasma in weak H. The energy stored both as gravitational potential energy and in the compressed H can be released suddenly because of plasma instability, which release leads to strong electric fields parallel with H, Joule heating, further ionization, and acceleration of electrons and protons along H, forming one or more jets. The jet 3C273A, for instance, could be formed in this way, with total energy of 10^{57} ergs (0.01 percent of the total energy of 3C273), and repeated every 12 years if the mass is 2×10^9 suns, the magnetic field H is 20,000 gauss, and the radius of the plasma (3C273B) is about 0.2 p. The jet particles would radiate when they strike an intergalactic gas cloud or an irregularity in H far from their source. Energy is available for thousands of such super-flares, and the process may be maintained by collection of intergalactic plasma in an open magnetic field. For instance, if the intergalactic plasma consists of 10^{-6} protons and electrons per cubic centimeter at temperature 10,000°K, the concentrated source collects 6×10^{26} g/sec, or 12.5 solar masses a year.

Recent observations give a better basis for these small, concentrated "plasma cores" of radio sources. B. G. Clark (NRAO) and H. P. Palmer (Jodrell Bank) reported interferometer measurements of $\theta < 0.4''$ in four instances, of $\theta < 1''$ in 16 others. Many of these very compact objects are double, with small separations, $\leqq 8''$. Palmer reported 3C273B as probably a double of separation 0.4″ and confirmed the increase in S of 30 percent in 3 years at $f = 1430$ Mc/sec ($\lambda = 21$ cm). T. Gold (Cornell) explained a double radio source as the result of two jets in opposite directions along an assumed intergalactic field of 10^{-5} gauss (somewhat more intense than others find reasonable). David Layzer (Harvard) predicts the acceleration of ions to cosmic-ray energies by interaction with reversed magnetic fields in two such plasma cores approaching one another.

C. Hazard (Australia) summarized his observations of Lunar occultations of 3C273, which achieved a resolution of 0.1″. With $f = 1$, 120, and 400 Mc/sec, there is no halo around 3C273B, and 3C273A has a bright patch at the far end, about 20″ from 3C273B; at 1430 Mc/sec the patch is centered about 15″ from 3C273B. In fact S. von Hoerner (NRAO) suspects changes in the structure of 3C273, from occultation observations over the past few years.

The changing radio flux was explained by A. G. W. Cameron (Insti-

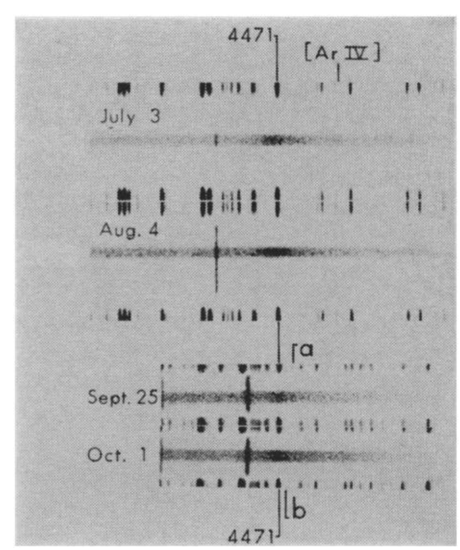

Fig. 3. Spectra of 3C345, taken with the Lick 120-inch telescope, showing variations in the wavelength and structure of the redshifted Mg-II λ2798 line. [Courtesy E. M. Burbidge]

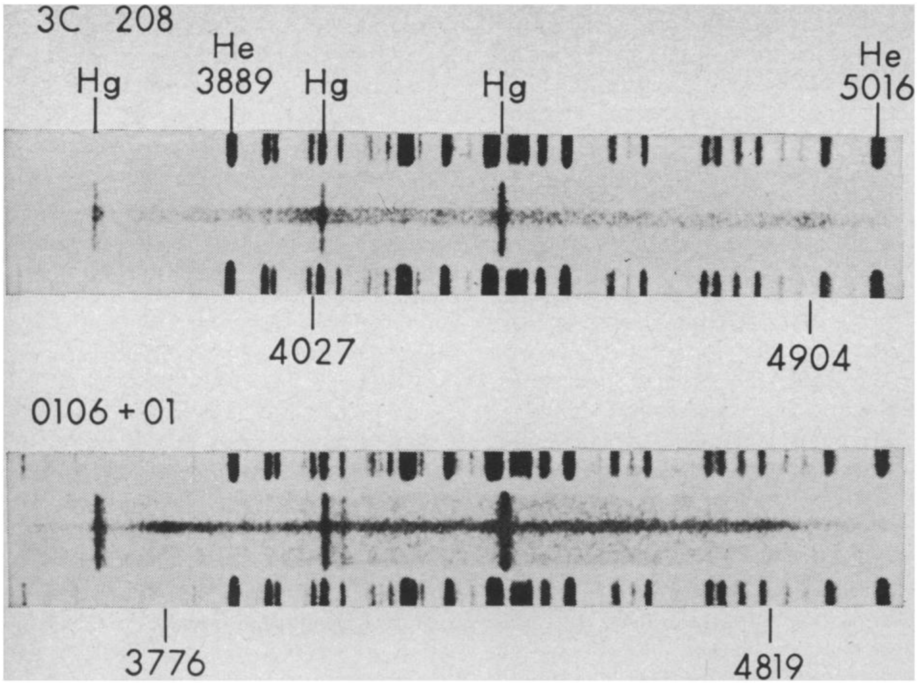

Fig. 4. Spectra of 3C208 (redshift, 1.109) and 0106+01 (redshift, 2.107), taken with the Lick 120-inch (305-cm) telescope. The two lines in 0106+01 are Lyman α and C IV, λ1550. [Courtesy E. M. Burbidge]

tute of Space Science) as the vibration of a gas cloud around a dense galaxy of stars. With turbulence of about 2000 km/sec over distance of 0.05 p in a mass of gas equal to 1.6×10^4 suns, stars totaling 10^{10} Suns, and magnetic fields $\leqq 38$ gauss, he finds a central gas density of 1.3×10^{15} g/cm^3 and a vibration period of 17 years. The energy available for radiation comes primarily from interaction between stars and gas, plus one supernova explosion per year. S. A. Colgate (New Mexico) reported similar calculations for a tightly packed galactic nucleus in which stellar collisions form large stars of 30 solar masses and produce ten supernovae per year in magnetic fields of 5 gauss. J. M. Bardeen (Caltech) reported a model of a rotating, super-massive star; if the rotation is uniform (like that of a solid body) the mass may be as great as 2×10^6 suns, and the luminosity would be proportional to mass, $\leqq 3 \times 10^{46}$ erg/sec, with surface temperature of 100,000°K and lifetime of 10^6 years. Calculations for larger rotating masses by von Hoerner showed the effects of turbulent friction of the central region, which leads to loss of mass in an equatorial rim, resulting in reduction of the angular momentum.

Fred Hoyle (Cambridge) discussed the forms of elliptical galaxies and quasars in terms of a modified steady-state cosmology developed by Hoyle, Burbidge, and Narlikar. This new theory involves local density fluctuations—deviations from the uniformity of earlier steady-state cosmology—that are expanding at a slower rate. The "C-field" responsible for continuous creation of matter in this theory is concentrated in regions of high mass density and exerts a pressure that prevents gravitational collapse, even of masses with zero rotation. Rough arguments lead Hoyle to expect density concentrations of 10^9 or 10^{10} suns in volumes of less than 1 p^3, and he showed that the gravitational field of such a massive nucleus would prevent the Hubble expansion of a mass equal to 10^{12} suns within about 3×10^4 p, similar to a giant elliptical galaxy. In more detail, the projected mass distribution is predicted to decrease with distance, r, from the nucleus and is proportional to $1/r^{5/3}$, which proportionality closely resembles the optical luminosity distribution in elliptical galaxies. He expects the nuclei of elliptical galaxies to be nonrotating. Hoyle argues that quasars are similar, but of even higher density, so that the C-field produces mass and energy at even higher rates.

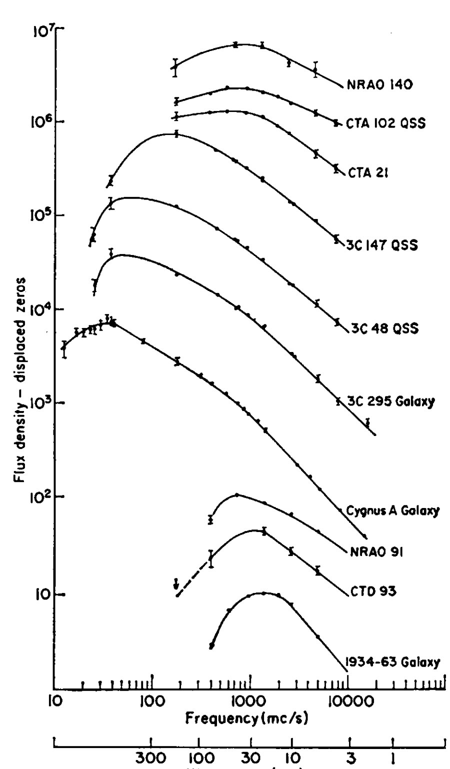

Fig. 5. Quasi-stellar objects: radio spectra. [Courtesy K. I. Kellerman]

Y. Ne'eman (Tel Aviv) also explains quasars as expanding more slowly than the Hubble expansions, but assumes a common origin at time $t = 0$ in evolutionary cosmology. Both Hoyle and Ne'eman ascribe the same age to all quasars—about 10^{10} years.

In all these theoretical studies the quasars are considered to be at great distances and consequently to have enormous luminosities and radio-power outputs. J. Terrell (Los Alamos) proposed that they are generally within 10^6 p rather than at $\geqq 10^9$ p; the power requirement is thus reduced by a factor of at least 10^6. He assumed that they were all ejected from the Milky Way Galaxy at high speeds about 5×10^6 years ago as a result of an explosion in the galactic nucleus, possibly powered by gravitational collapse. The optical emission-line widths observed are consistent if one assumes masses of about 10^4 suns, radii of 3×10^{-5} p, and rotation under self-gravitational stability. The high speed of such an object through an intergalactic gas of 10^{-29} g/cm^3 (1 H atom per 10^5 cm^3) would give radio emission over a shock-wave region about 1 p across, with power output about 10^{37} erg/sec. However, McCrea (London) pointed out that Terrell's model could not readily explain the increasing numbers of quasars with larger redshifts and smaller flux densities. Schmidt questioned the energy required for the initial explosion to eject 50 quasars at speeds near 10^5 km/sec: If this was as great as 10^{61} ergs, why not explain quasars as other galaxies doing the same?

In summary, the quasars (excluding

Sciama's small galactic radio sources) lie probably at great distances consistent with the Hubble law applied to their redshifts. Their variability implies smaller internal concentrations, possibly super-massive stars or super-dense nuclei with flares or jets or short pulsation periods. The optical spectra indicate low-density gas highly excited by radiation, and the radio spectra indicate highly ionized gas in a magnetic field. Their energy store is probably gravitational and magnetic, possibly with contributions from turbulence and nuclear reactions in supernovae. The synchrotron mechanism can account for radio emission and its variability, but the optical properties are less well understood.

Radiation, Primordial Material, and Cosmology

In addition to optical and radio observations, it has recently become possible to observe x-rays and γ-rays from astronomical sources (as well as the high-energy cosmic rays studied for more than 40 years). E. A. Spiegel (New York) noted that high-speed motion of a star (or of any other massive body such as Terrell's fragments from the Milky Way nucleus) through low-density gas will be supersonic, producing a high-temperature jet. He had calculated that an elliptical galaxy moving at supersonic speed through intergalactic hydrogen (assumed density, 10^{-5} atoms/cm^3) will produce a detectable x-ray source. Another possible source of high-energy background radiation is photon-photon interaction in empty space, discussed by R. J. Gould (San Diego), who pointed out that the interaction probability is significantly high for energies greater than 10^{14} ev during 10^{10} years. J. Felton (San Diego) expects a γ-ray background-intensity proportional to $1/(\text{energy})^{1.3}$, due to high-energy electrons ejected by quasars in an intergalactic magnetic field of 10^{-6} gauss.

The radiation density and material content of intergalactic space depend strongly on the past history of the universe and on the cosmological model adopted to interpret current observations. Quanta emitted billions of years ago, for instance, have suffered large redshift and possible absorption by intergalactic gas, but still reflect conditions that may have been the same as those today (in steady-state cosmology) or very different (in evolutionary cosmologies). R. W. Wilson (Bell Laboratories) described the accurate measurement of background radiation at 4300 Mc/sec ($\lambda = 7$ cm) with a corner-reflector antenna of 97-percent efficiency. After making accurate corrections for Earth's atmospheric effects, instrumental noise, and such, he and Penzias obtained a sky background temperature of 3.1°K ± 0.3°. P. Roll (Princeton) extended this to 9370 Mc/sec ($\lambda = 3.2$ cm), where $T = 2.5$°K ± 0.5°. George Field (Berkeley) pointed out that recent measurements of interstellar CN-absorption bands in star spectra imply a radiation temperature of 3°K at $\lambda = 0.254$ cm in interstellar space.

P. J. E. Peebles (Princeton) discussed two theoretical explanations of the background radiation: one based on the high temperature of all matter in the universe shortly after the "big bang" in evolutionary cosmology (the Einstein-de Sitter model), the other based on radiation from hot interstellar hydrogen. The first leads to a predicted abundance of helium about twice as great as that observed; the second leads to a predicted variation of background T with λ, contrary to the measurements of Penzias, Wilson, and Roll.

At $t = 0.01$ second after the big bang, according to Peebles' calculations, the temperature was (10^{11})°K and the radiation density was 10^{3} quanta/cm^3 in thermodynamic equilibrium with a high-density gas of proton and electrons. At $t = 10^3$ second, $T = 3 \times 10^9$, and nuclear reactions had built up neutrons, neutrinos, deuterium, and helium (alpha particles). As time went on, the relative abundances changed: neutrons decreased in number, deuterium went through a maximum, and helium increased. At some moment the material became transparent to radiation and halted the changes in abundances. The temperature at that moment was the "fireball" temperature responsible for background radiation, which has decreased adiabatically as the universe has expanded ever since, resulting in a low background temperature, T_r, today, which is the same at all wavelengths. Peebles had expected $T_r \cong 10$°K, which temperature is associated with a helium abundance of 15 percent by weight and deuterium abundance of 10^{-4}. The observed value for T_r, 3°K, implies 30 percent helium and no deuterium in the primordial gas from which present galaxies and stars were formed.

David Layzer (Harvard) had reached a different conclusion; taking account of quantum statistics in the early stages of expansion, he had found that T_r varies with λ, and that early values of T changed in a different way, probably leading to different abundances. Later condensation of galaxies he can explain by gravitational instability in an expanding homogeneous medium.

Peebles' second calculation concerns the effect of absorption and emission of quanta, by ionized hydrogen, due to free-free transitions (changes of an electron's energy near a proton), which absorption and emission occurred mainly during the early, high-temperature stage of evolutionary cosmology. Assuming that the free electrons were then at a temperature of 10^6, he and R. H. Dicke (Princeton) showed that background-radiation quanta detected today were emitted when the density of the universe was about 10^{-15} g/cm^3, about 1000 years after the "big bang," and that T_r should be proportional to $\lambda^{\frac{4}{5}}$. That is, 7-cm quanta observed today were 1400-Å quanta emitted about 10^{10} years ago in larger numbers than 500-Å quanta now detectable as 0.25-cm background radiation. If $T_r = 3°K$ at $\lambda = 7$ cm, Dicke and Peebles predict $T_r = 0.2°K$ at $\lambda = 0.25$ cm, instead of the 3°K observed.

Although the calculations of early intergalactic absorption are not well confirmed, there was interest in possible intergalactic absorption of light from quasars more than 10^9 light years distant. J. E. Gunn (Caltech) showed that the partial absorption (about 40 percent in 3C9), at wavelengths shorter than the redshifted Lyman-alpha line in Schmidt's and Burbidge's spectra, imply no more than 6×10^{-11} atoms of intergalactic hydrogen per cubic centimeter (10^{-34} g/cm^3), whereas evolutionary cosmology requires about 10^{-28} g/cm^3, with cosmological constant zero. Of course, if the intergalactic material were at high temperature, $T \approx 100{,}000°K$, most of the hydrogen would be ionized, and the density could be 10^{-28} with the observed Lyman-alpha absorption. But in this case Thompson scattering by free electrons would be noticeable at redshift $z > 2$, and would obliterate images for $z \geqq 5$. J. N. Bahcall (Caltech) noted that intergalactic gas in a cluster of galaxies should have less velocity dispersion than gas along the line of sight; the spectrum of a quasar behind a cluster may show fairly sharp absorption lines at the resonant absorption wavelengths of H, CIV, CIII, and MgII ($\lambda\lambda$ 1216, 1550, 1909, and 2789, respectively, with the cluster redshift).

Finally, N. Woolf (Texas) summarized evidence from the last 30 years of astrophysical research that the universal helium abundance is less than the value of 30 percent calculated by Peebles from the background-radiation measurements. Helium abundance is measured directly only in the atmospheres of hot, young, Population-I stars where the abundance Y is about 40 percent. One hot, B2, Population-II star in the globular cluster M13 has $Y = 20$ percent, and the plot of temperature versus luminosity for old Population-II stars in another globular cluster, M3, is consistent with $Y = 13$ percent. Since helium is found in stellar interiors and is returned to the interstellar medium by supernova explosions, it is generally concluded that the primordial gas clouds, from which the first stars were formed, were pure hydrogen ($Y = 0$). Woolf noted that these first-generation "Population-III" stars in our galaxy were probably large (10 solar masses) and short-lived (about 10^7 yr). They returned material to the interstellar medium with various amounts of helium added, and thus obscure the original helium abundance. He thinks that smaller Population-III stars would have been formed in dwarf galaxies or in intergalactic globular clusters, where abundances measured today may reflect the original amounts of helium more accurately.

In summary, recent observations of background radio radiation and strongly redshifted ultraviolet spectra of quasars have provided new data for checking cosmological theories; the data show fairly serious inconsistencies. One central set of questions concerns the intergalactic medium: What is its density? Temperature? Composition? How has it affected the background radiation from a primordial "fireball"? Most attempts to answer these questions are based on the Einstein-de Sitter evolutionary model, which starts about 10^{10} years ago with a big bang. Other cosmologies, such as Dicke's with time-dependent gravitation, would give different answers, and in steady-state cosmology some of the questions themselves disappear.

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