PULSARS

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Late in 1967 astronomers at Cambridge, England, discovered pulsars. They were found by a graduate student who was studying interstellar scintillation with a large array operating at low frequencies. Initially four pulsars were found in this way. Since that time the number of known pulsars has grown to 50 and observations have provided much information on the processes involved.

The basic properties of pulsars are as follows:

1) Intense short duration pulses with a duty cycle of about 5%.

2) Great regularity in the pulse repetition rate.

3) Apparently erratic variation in the pulse amplitude.

Pulsar radiation is dispersed by the interstellar medium--lower frequencies propagate with a smaller velocity and so arrive later.

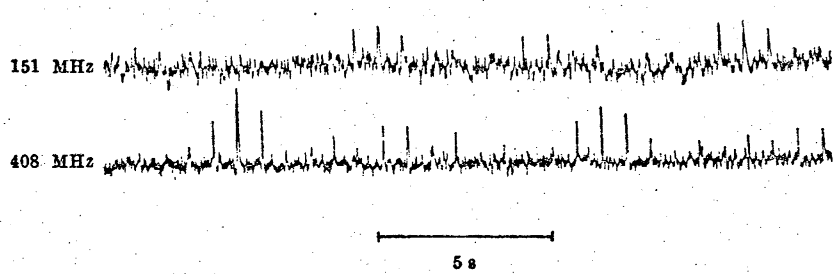


Fig. 3. A fast galvanometer recording of a train of pulses from *CP* 0328 received simultaneously at frequencies of 151 MHz and 408 MHz (on August 4). The dispersion delay of nearly six periods is evident.

The <u>dispersion</u> <u>measure</u> for a given pulsar is defined by

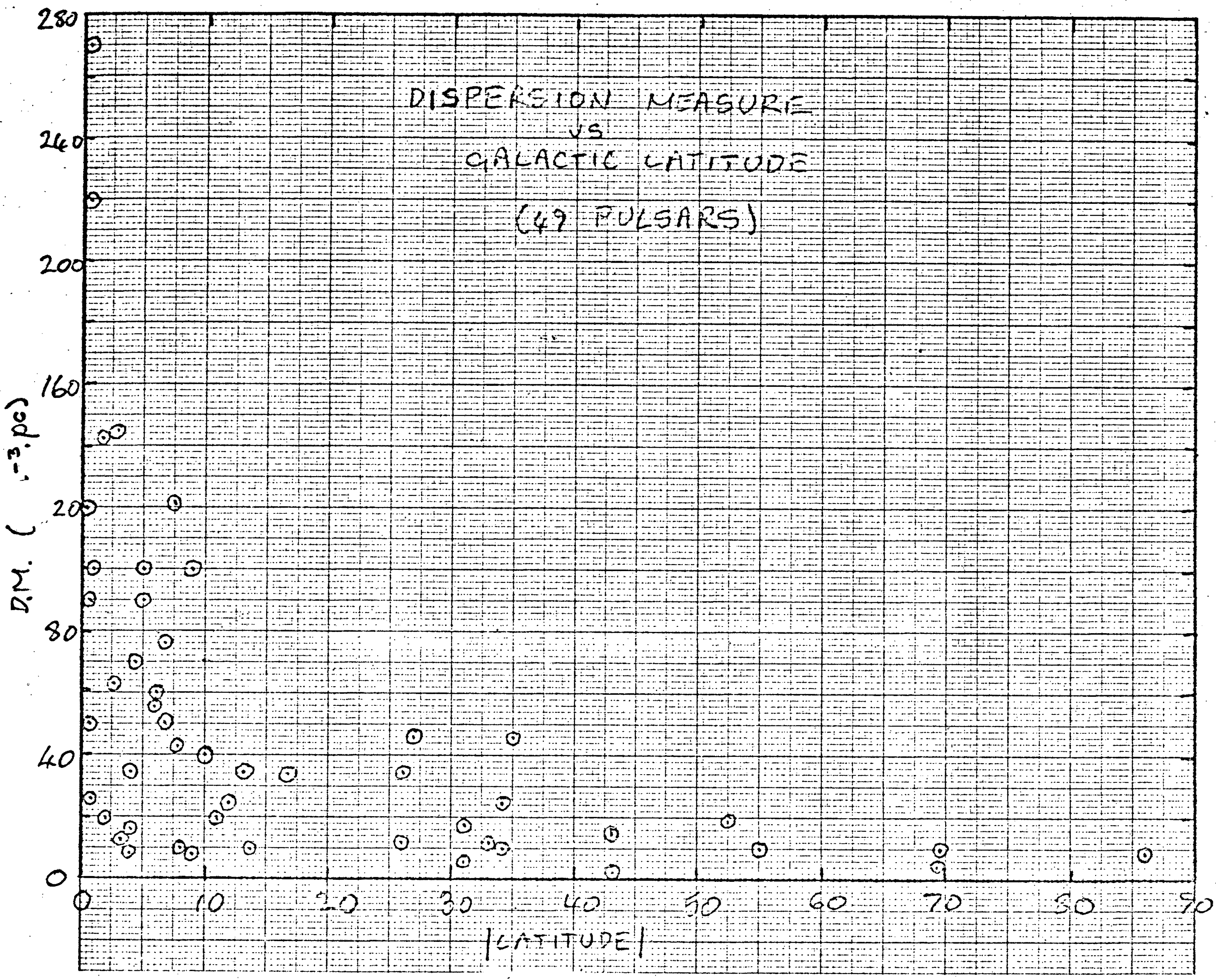
$$DM = \int_{path} n_e \, d\ell = 2.41 \times 10^{-16} \left(\frac{t_i - t_j}{\nu_i^{-2} - \nu_j^{-2}} \right)$$

where n_e = electron density (cm^{-3})

$d\ell$ = element of path (pc)

t_i, t_j = arrival time (sec) of pulse at frequency ν_i, ν_j (Hz).

The variation of dispersion measure with galactic latitude shows that pulsars are confined to our galaxy but are widely distributed through it.



This is also shown by the distribution of the pulsars in space--there is a considerable clustering of pulsars along the galactic plane.

As pulsars have a very stable period, the signal/noise ratio of observations can be improved by averaging together many pulses. The mean pulse profile obtained in this way remains the same for a given pulsar but differs greatly from one pulsar to another. Observations with orthogonal feeds show that the pulses are often highly linearly polarized with systematic variations of the polarization parameters across the pulse. As these mean pulse profiles do not differ from day to day they must be determined by the emitting regions at the pulsar and not by propagation effects.

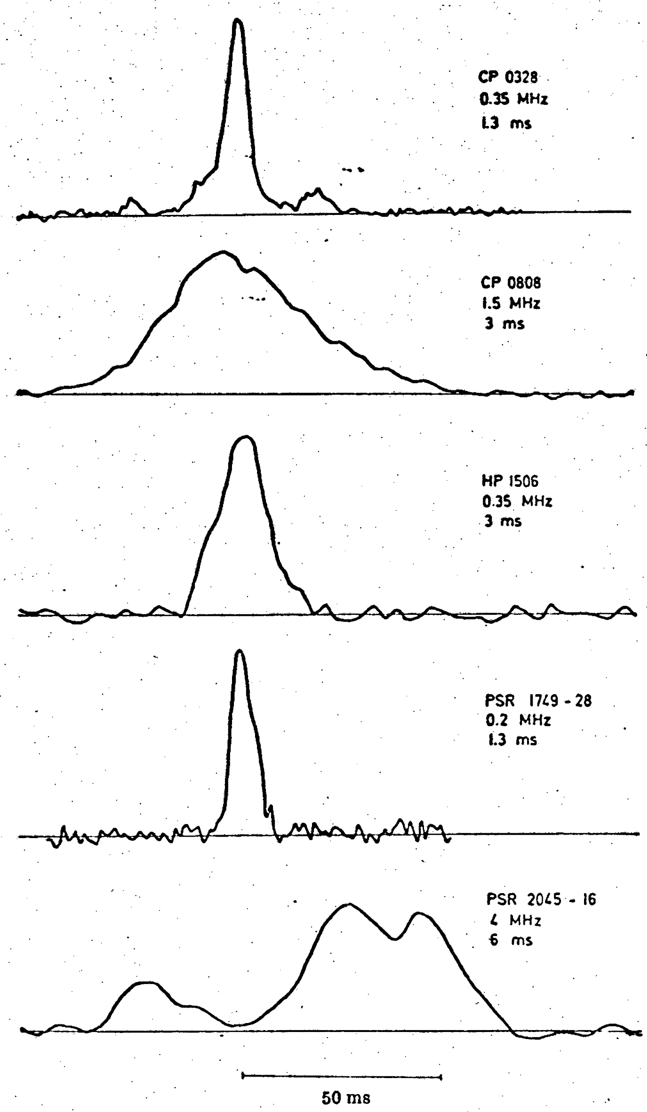


Fig. 5. Mean pulse profiles at 408 MHz over periods of 10 min on the ˋve pulsars. For each source the bandwidth and overall resolution, including dispersion and time constant, are indicated. The aerial polarization was circular for the first three and linear for the other two.

Single pulse observations show that the pulse often has very narrow spikes of emission, in some cases as narrow as 100 μs. Variations in intensity this short put strong limits on the size of the emitting region, as the region cannot be much larger than the distance light would travel during the rise of the spike. In this case the limiting size is about 30 km.

Observations of successive individual pulses have also shown that, for several pulsars, a series of subpulses shift steadily across the main pulse.

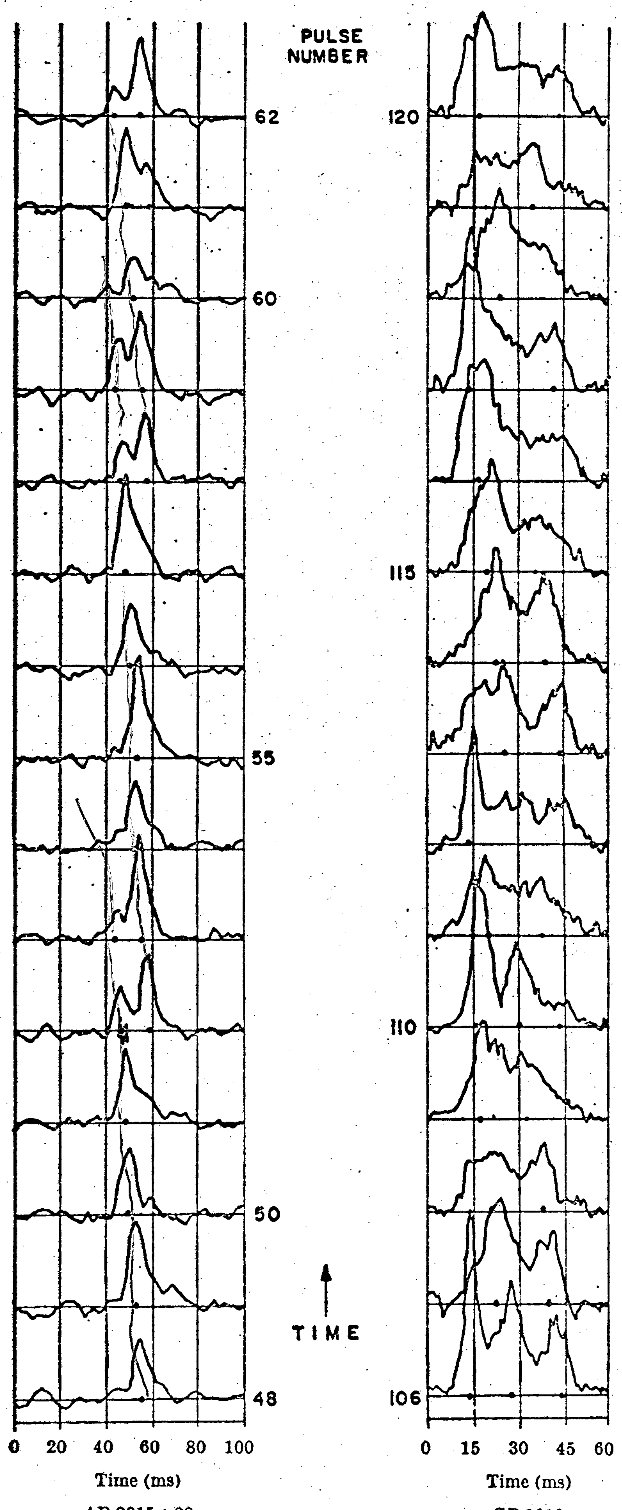


Fig. 1. Pulse shapes of fifteen consecutive pulses from the pulsars *AP* 2015+28 and *CP* 1919. Observed with time constants of 2·6 and 1·0 ms, on September 10 and August 26, 1968, respectively, and at a radio frequency of 428·5 MHz. The points designate the intrapulse time of subpulse maxima. Small points indicate that the time of maximum subpulse intensity is poorly defined.

In all cases where this effect has been observed, the subpulses move backwards through the mean profile. This effect can introduce a periodic variation into the pulse amplitude. Scintillation effects in the interstellar medium produce irregular fluctuations in the pulse intensity. After scattering by clouds of interstellar gas some of the radiation interferes constructively producing strong pulses, while some interferes destructively producing weak pulses. Power spectrum analysis can be used to find the periodic components in the pulse amplitude variations. So far they have been found in about one-third of the known pulsars.

Scintillation also affects the spectrum of the pulsar radiation. Some frequency ranges are enhanced by the constructive interference while some others are depressed. The enhanced bands tend to last for several minutes and then die out with a new band appearing at a different frequency.

If the power averaged over all scintillation effects is measured at a number of frequencies, the overall spectrum of the radiation can be determined. In all cases the power is less at higher frequencies; however the falloff is faster in some pulsars than in others. These measurements are complicated by the fact that the mean pulse intensity at a given frequency can often vary by large amounts, sometimes greater than an order of magnitude, over periods of a few weeks.

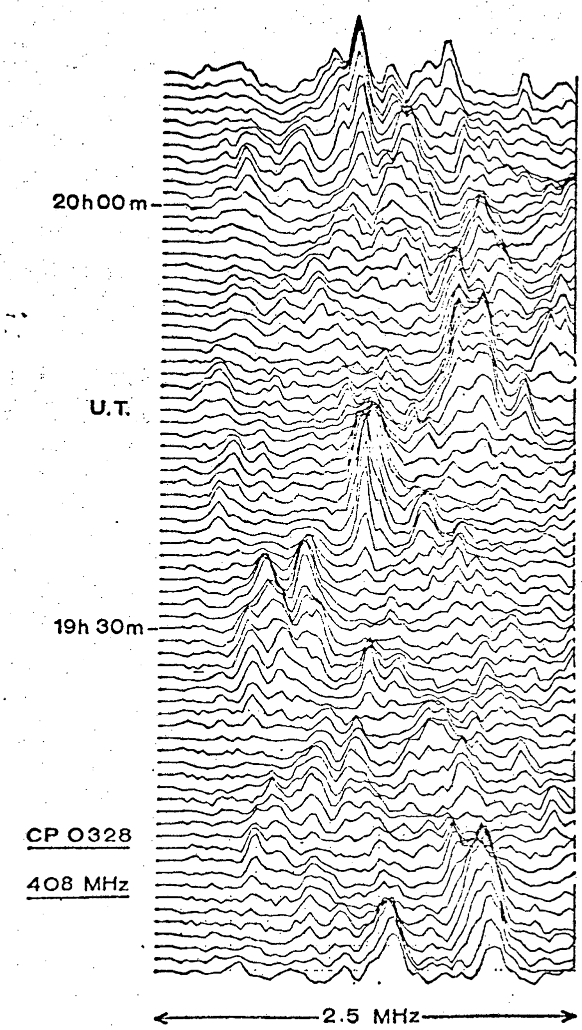


Fig. 1. Successive mean pulse spectra from *CP* 0328 at 408 MHz at intervals of about 50 s. The frequency resolution is 60 kHz and the spectra include the effect of the receiver pass-band.

Timing

The most noteworthy thing about pulsars is their extremely stable pulse repetition rate. Observations have shown that in most pulsars the period is slowly increasing. For example the Crab Nebula pulsar (which has the shortest known period) had a period of

$$0\overset{s}{.}033\ 099\ 324\ 10 \quad \pm\ 0\overset{s}{.}000\ 000\ 000\ 05$$

at 00^h on June 27, 1969, and a rate of increase of period of

$$422.66 \times 10^{-15}\ \text{s/s or } 36.518\ \text{ns/day}.$$

Generally those pulsars with the shortest period have the fastest rate of slowdown. To obtain these very accurate periods and period derivatives the pulsar must be observed for a long period. Times of pulse arrival calculated using an assumed period are compared with those observed and new parameters are calculated so that the differences between the calculated and observed values are minimized. If the period has a significant rate of change the residuals form a parabola and the period first derivative can be calculated from the shape of the parabola.

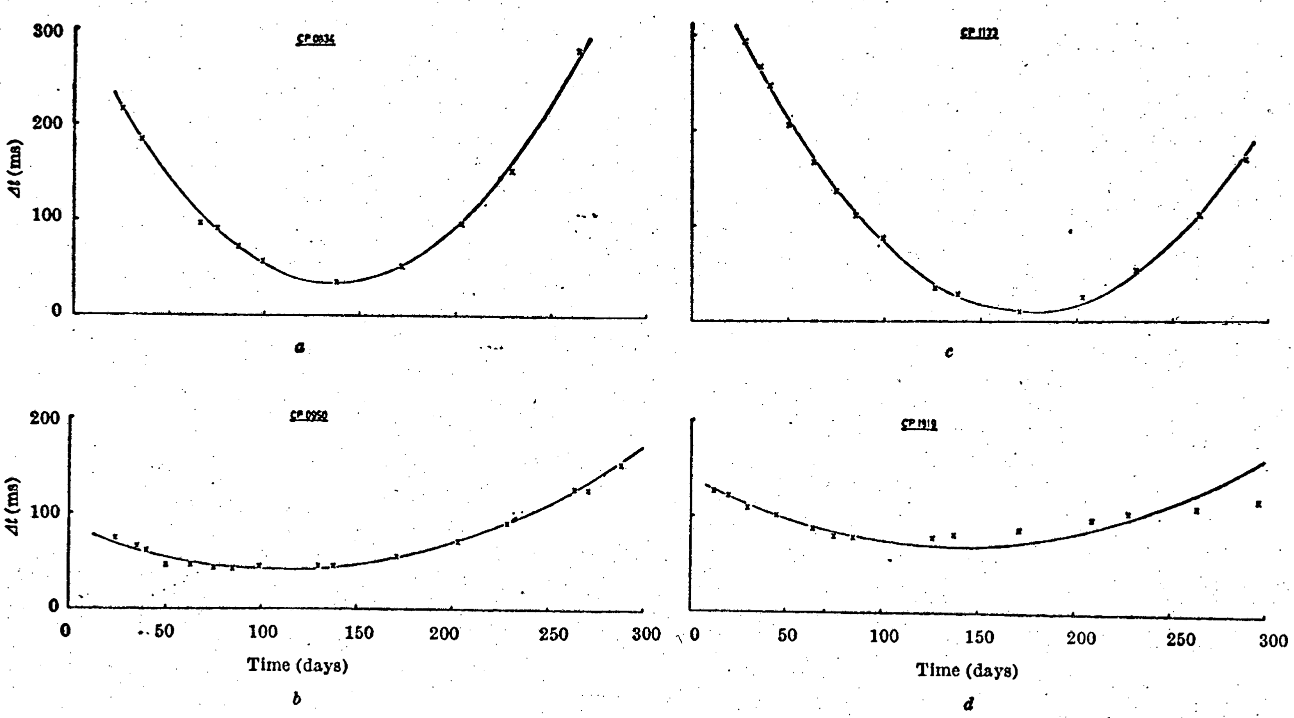


Fig. 1. Difference Δt between measured and predicted arrival times for four pulsars: (*a*) *CP* 0834, (*b*) *CP* 0950, (*c*) *CP* 1133, (*d*) *CP* 1919. The initial date is Julian Day 2439900·5 (February 14, 1968).

Pulsars are not always so predictable. During March, 1969, the period of the Vela pulsar suddenly decreased by about 200 ns, and then resumed its regular increase. Since then the Crab Nebula pulsar has also suffered a similar but smaller jump.

The pulsar in the Crab Nebula has been the most intensively studied and is the most interesting for a number of reasons.

i) It has the shortest known period and the largest known rate of change of period.

ii) It is the only known pulsar associated with an optically visible object--the Crab supernova. The pulsar in Vela is the only other for which the pulsar-supernova association is reasonably certain.

iii) It is the only pulsar from which pulses of visible light have been observed.

iv) Similarly, it is the only one from which pulsed x-rays have been observed.

Models

Of the many models proposed for pulsars only one, the rotating neutron star, appears to fit all the observational data. In this model the pulsed nature of the radiation is accounted for by a narrow beam from the star sweeping past the observer as the star rotates--the so-called lighthouse effect. The material of the star must be very dense to prevent the star bursting apart at the high rotational velocities observed. It is thought that neutron stars have about the same mass as the sun, but a diameter of only about 10 km; that is, a density of 100,000,000 tons/cm^3.

Neutron stars are thought to be the condensed remnant of a star, formed following a supernova explosion. As the magnetic field remains frozen in during the collapse of the star, the magnetic field of a neutron star will be very large--about 10^{12} gauss at the surface of the star. In general the magnetic axis will not coincide with the rotation axis, so we have the "oblique rotator" model for pulsars.

The pulsed emission from the pulsar must be generated within the "velocity of light cylinder"; that is, the cylinder aligned along the rotation axis at which the tangential velocity due to rotation equals the velocity of light. Beyond this surface the magnetic field and plasma cannot co-rotate with the star. Observations of polarization changes across the pulse indicate that the emission probably originates close to a magnetic pole. Because of the curvature of the field line, ultra-relativistic particles moving out from the pole along a field line radiate a narrow beam at radio frequencies in the direction of their instantaneous velocity. If the particles are gyrating round the field lines they will also radiate optical synchrotron radiation. Coherent processes are required to account for the pulse intensities observed.

This model explains the very stable pulse repetition rate and the slow increase in period. Because of dissipation of energy in various radiation processes the rotation is gradually slowing down, resulting in a slow increase in period. The period jumps seen in the Vela and Crab pulsars are thought to be due to a small star-quake on the neutron star. A decrease in radius of only 1 cm is sufficient to account for the speed-up observed in the Vela pulsar.

NGC 7822

(W 1)

G. Westerhout; BAN 14, 215 (1958)
Flux at 1390 MHz

S. Sharpless; Ap. J. Supp. 4, 257 (1959)
List of 313 HII regions

R.W. Wilson, J. G. Bolton; P.A.S.P. 72, 331 (1960)
Flux at 960 MHz

A.D. Kuzmin, et al.; Soviet A.J. 4, 909 (1961)
Flux at 3125 MHz

C.R. Lynds; Pub. NRAO 1, 43 (1961)
Flux at 1400 MHz

R.W. Wilson; Ap. J. 68, 181 (1963)
Flux at 960 MHz

W.E. Howard III, S. P. Maran; Ap. J. Supp. 10, 1 (1964)
#1 in list

J.L. Caswell; M.N.R.A.S. 137, 141 (1967)
Flux at 178 MHz

N.H. Dieter; Ap. J. 150, 435 (1967)
Electron temp. from 158-alpha line

W. M. Goss; Ap. J. Supp. 15, 131 (1967)
OH position

E. Churchwell, B. Felli; Astron. and Astrop. 4, 309 (1970)
Flux at 5.0 and 1.4 GHz

NGC 1491

(CTB 12)

W. E. Howard III, S. P. Maran; Ap. J. Suppl. 10, 1 (1964)
#137 in list

C. Field; M.N.R.A.S. 137, 419 (1967)
Compute electron temp. and emission measure

NGC 6523, 6530

(M 8)

B. J. Bok, E. F. Reilly; Ap. J. 105, 225 (1947)
Remarks on existence of small, dark globules

A. D. Thackery; M.N.R.A.S. 110, 343 (1950)
Observations of bright rims around dark lanes

G. A. Schajn, W. F. Hase; Proc. USSR Acad. Sci. (Doklady) 83, 47 (1952)
Mass of M 8 = 5300 M (sun)

G. A. Schajn, W. F. Hase; Mitt. Astrophys. Ob. Krim. 8, 80 (1952)
Mass = 3200 M (sun) and Ne = 53 cm^{-3}

G. Courtes; Comptes Rendus 238, 1971 (1954)
Comparison of radial velocity of stars and nebula

S. Pottasch; BAN 13, 77 (1956)
Discusses bright rims and relation to exciting stars

D. H. Schulte; Ap. J. 123, 250 (1956)
Objective grating spectra of Herschel 36

G. H. Herbig; Ap. J. 125, 654 (1957)
Position of emission line stars in M 8

D. E. Osterbrock; Ap. J. 125, 622 (1957)
List of comet-tail structures

A. G. Velghe; Ap. J. 125, 822 (1957)
Finding chart for two bright knots close to Herschel 36

A. G. Velghe; Ap. J. 126, 302 (1957)
Positions of H-alpha emission stars

M. F. Walker; Ap. J. 125, 636 (1957)
UBV observations of 118 starts in NGC 6530

S. Sharpless; Ap. J. Supp. 4, 257 (1959)
List of 313 HII regions

W. I. Pronik; Mitt. Astrophys. Obs. Krim. 23, 3 (196
Electron temp. and star membership in M 8

N. J. Woolf; P.A.S.P. 73, 206 (1961)
Discussion of Herschel 36

W. E. Howard III, S. P. Maran; Ap. J. Supp. 10, 1 (1964)
#517 in list

W. A. Hiltner, et al.; Ap. J. 141, 183 (1965)
Brighter stars of NGC 6530 are classified between 05-B3

NGC 6523, 6530 (continued)

N. H. Dieter; Ap. J. 150, 435 (1967)
Electron temp. from 158-alpha recombination line

W. M. Goss; Ap. J. Supp. 15, 131 (1967)
OH positions

P. G. Mezger, A. P. Henderson; Ap. J. 147, 471 (1967)
Flux at 6 cm.

P. G. Mezger, B. Höglund, Ap. J. 147, 490 (1967)
Electron temp. from 109-alpha recombination line

M. Peimbert; Ap. J. 150, 825 (1967)
Discusses possible reasons why different methods give different values of electron temp.

A. A. Cummingham; Ap. J. 151, 945 (1968)
Gives distribution of N_e

P. Foukal; Astroph. and Space Sci. 4, 127 (1969)
Core expanding from H-alpha and [NII] observations

R. Louise, G. Monnet; Astron. and Astroph. 1, 153 (1963)
Electron temp. from H-alpha and [NII] lines

D. K. Milne, E. R. Hill; Ans. J. Phys. 22, 211 (1969)
Relation to superova remnants

Anderson; Ap. J. 160, 507 (1970)
Reddening of Herschel 36 and HD 164906

V. Petrosian; Ap. J. 159, 833 (1970)
Electron temp. from IR lines

E. C. Reifenstein III, et al.; Astron. and Astroph. 4, 357 (1970)
Electron temp. from 109-alpha line

B. E. Turner, et al.; Astron. and Astroph. 4, 165 (1970)
Find no H_2O emission

NGC 1499

N. U. Mayall; P.A.S.P. 65, 152 (1953)
Radial velocity of cloud and exciting star

S. Pottasch; BAN 13, 77 (1956)
Discusses bright rims and diagrams thru relation to exciting stars

S. Sharpless; Ap. J. Supp. 4, 257 (1959)
Gives list of 313 HII regions

C. K. Seyfert, et al.; Ap. J. 132, 58 (1960)
Gives spectral types of early stars in II Persei association

C. R. Lynds; Pub. NRAO 1, 43 (1961)
Flux at 1400 MHz

Y. Terzian; Pub. NRAO 1, 1205 (1962)
Flux at 750 MHz

W. E. Howard III, S. P. Maran; Ap. J. Suppl. 10, 1 (1964)
#136 in list

C. Field; M.N.R.A.S. 137, 419 (1967)
Electron temp. and emission measure

NGC 7538

C. R. Lynds; Pub. NRAO, 1, 43 (1961)
Flux at 1400 MHz

J. Schraml, P. G. Mezger; Ap. J. 156, 269 (1969)
General discussion of HII regions. Contour map at 1.95 cm.

NRAO 591/593

D. O. Edge _et al._; Mem. R.A.S. 68, 37 (1959)
Flux at 159 MHz for NRAO 593

I.I.K. Pauliny-Toth _et al._; Ap. J. Supp. 13, 65 (1966)
Flux at 750 and 1400 MHz

P.J.S. Williams, _et al._; Mem. R.A.S. 70, 53 (1966)
Flux at 38 MHz for NRAO 593

E. B. Fomalont; Ap. J. Supp. 15, 203 (1967)
Flux at 1425 MHz

J.F.R. Gower; Mem. R.A.S. 71, 49 (1967)
Flux at 178 MHz

V.A. Hughes; Jour. R.A.S. Canada 62, 192 (1968)
Dimensions for NRAO 591 and 593.

D. Ristow; Beiträge zur Radio-Astronomie (Bonn) 1, 65 (1968)
NRAO 591/593 not observed at 2695 MHz down to 0.2 f.u.

V.A. Hughes, R. Bulter; Ap. J. 155, 1061 (1969)
General discussion for NRAO 591/593

NGC 6611

(M 16)

A. D. Thackery; M.N.R.A.S. 110, 343 (1950)
Observations of bright rims around dark lanes

S. Pottasch; BAN 13, 77 (1956)
Discusses bright rims and relation to exciting stars

D. E. Osterbrock; Ap. J. 125, 622 (1957)
Gives list of comet-tail structures and exciting stars

G. Westerhout; BAN 14, 215 (1958)
Flux at 1390 MHz

S. Sharpless; Ap. J. Supp. 4, 257 (1959)
List of 313 HII regions

M. F. Walker; Ap. J. 133, 438 (1961)
UBV observations of 532 stars. Also shows positions of variables in nebula

W. E. Howard III, S. P. Maran; Ap. J. Supp. 10, 1, (1964)
#527 in list

Y. Terzian; Ap. J. 142, 135 (1965)
Observations at 405, 750 and 234 MHz. Gives brightness contours at 1410 MHz

N. H. Dieter; Ap. J. 150, 435 (1967)
Electron temp. from 158-alpha list

J. E. Dyson; Ap. J. 150, L 45 (1967)
Electron temp. obtained using non-LTE

W. M. Goss; Ap. J. Supp. 15, 131 (1967)
OH position

P.G. Mezger, A. P. Henderson; Ap. J. 147, 471 (1967)
Flux at 6 cm

P.G. Mezger, B. Hoglund; Ap. J. 147, 490 (1967)
Electron temp. from 109-alpha line

A. A. Cummingham; Ap. J. 151, 945 (1968)
Distribution of electron density, and estimates an expansion age

M. E. Sim; Pub. Royal Ob., Edinburgh 6, 181 (1968)
Finds 3 "certain" globules, 3 "probable" and 2 "doubtful" in M16

W. A. Hiltner, W. W. Morgan; Ap. J. 74, 1152 (1969)
Photometry and spectral types of 15 stars

R. Louise, G. Monnet; Astron. and Astrop. 1, 153 (1969)
Electron temp. from H-alpha and [N II] lines

B. Felli, E. Churchwell; Ap. J. 160, 43 (1970)
Flux at 15.4 GHz

R. M. Hjellming, R. D. Davies; Astron. and Astrop. 5, 53 (1970)
Electron temp. from recombination lines

E. C. Riefenstein III et al.; Astron. and Astrop. 4, 357 (1970)
Electron temp. from 109-alpha line

NGC 2024

(Orion B)

S. Sharpless; Ap. J. 116, 251 (1952)
Spectra and luminosity classification for 190 stars of Orion group

S. Sharpless; Ap. J. 119, 200 (1954)
Spectral class for 184 stars

W. W. Morgan; Ap. J. 121, 611 (1955)
Photographs of Orion and other nebulae

H. Rishbeth; M.N.R.A.S. 118, 591 (1958)
Isophotes at 19.7 and 85.5 MHz

G. Westerhout; BAN 14, 215 (1958)
Flux at 1390 MHz

L. J. Robinson; Sky and Tel. 19, 152 (1959)
Finding chart for variables in and around Orion region

A. S. Bennett; Mem. R.A.S. 68, 163 (1962)
Flux at 178 MHz

J. S. Hall, B. Iriarte; Bul. Tonantzintla y Tacubaya 3, 336 (1964)
Find polarization of 0.22 Mag for a star (for finding chart, see article below)

H. L. Johnson, E. E. Mendoza; Bul. Tonantzintla y Tacubaya 3, 331 (1964)
UBVRIJK observations of a highly reddened O-B star

W. E. Howard III, S. P. Maran; Ap. J. Supp. 10, 1 (1965)
#199 in list

N. H. Dieter; Ap. J. 150, 435 (1967)
Electron temp. from 158-alpha recombination line

P. G. Mezger, A. P. Henderson; Ap. J. 147, 471 (1967)
Observations at 6 cm

P. G. Mezger, B. Hoglund; Ap. J. 147, 490 (1967)
Electron temp. from 109-alpha recombination line

B. Zuckerman et al.; Ap. J. 149, L61 (1967)
Conclude nebula not in LTE from observations of 109-alpha and 137-beta

F. F. Gardner, M. Morimoto; Ans. J. Phys. 21, 881 (1968)
Flux at 5 GHz

R. F. Garrison; P.A.S.P. 80, 20 (1968)
Spectrum of highly reddened star [see top of this page] is B0.5 V p

NGC 2024

(Orion B) continued

P. G. Mezger, S. A. Ellis; Astrophy. Letters, 1, 159 (1968)
Electron temp. from 109-alpha recombination line

Y. Terzian et al.; Astrophy. Letters, 1, 153 (1968)
Flux at 74, 195, 430, 750, 1410, and 15350 MHz

B. Zuckerman, P. Palmer; Ap. J. 153, L 145 (1968)
Discuss microwave recombination lines

M. A. Gordon; Ap. J. 158, 479 (1969)
Observations of 94-alpha recombination line, doesn't think eta Ori is the exciting star

J. Schraml, P. G. Mezger; Ap. J. 156, 269 (1969)
Contour map at 1.95 GHz

B. E. Turner; A. J. 74, 985 (1969)
OH not found

R. M. Hjellming, R. D. Davies; Astron. and Astrophys. 5, 53 (1970)
Get electron temp. from recombination lines

E. C. Reifenstein III et al.; Astron and Astrophys. 4, 357 (1970)
Electron temp. from 109-alpha recombination line

NGC 2237-2246

(Rosette)

G. A. Schajn, W. F. Hase; Proc. USSR Acad. Sci. (Doklady) 83, 47 (1952)
Mass of NGC 2237 = 10^4 M (sun)

G. A. Schajn, W. F. Hase; Mitt. Astrophy. Obs. Krim. 8, 80 (1952)
For NGC 2237, get mass = 5800 and N_e = 28 cm^{-3}

H. C. Ko, J. D. Kraus; Nature 176, 221 (1955)
Flux for NGC 2244 at 242 MHz

W. W. Morgan, et al.; Ap. J. 121, 611 (1955)
Photographs of Rosette and other nebulae

S. Pottasch; BAN 13, 77 (1956)
Discusses bright rims and their relation to exciting stars

C. L. Seeger, et al.; BAN 13, 89 (1956)
Flux for Rosette at 400 MHz

G. Westerhout; BAN 14, 215 (1958)
Flux at 1390 MHz for NGC 2244

A. A. Hoag; E. v. P. Smith; P.A.S.P. 71, 32 (1959)
Photoelectric photometry of 63 stars in NGC 2244

S. Sharpless; Ap. J. Supp. 4, 257 (1959)
List of 313 HII regions

D. E. Harris, J. A. Roberts; P.A.S.P. 72, 237 (1960)
Flux at 960 MHz

L. R. Allen, et al.; M.N.R.A.S. 124, 477 (1962)
Observations at 158 MHz with long base ine interferometer

H. L. Johnson; Ap. J. 136, 1135 (1962)
Photoelectric measurement of 46 stars in NGC 2244

A. D. Kuzmin; Pub. Phys. Inst. USSR Acad. 17, 84 (1962)
Observations at 9.6 cm give density of 12 cm^{-3}

T. K. Menon; Ap. J. 135, 394 (1962)
Observations at 10 cm give density of 13.7 cm^{-3}

R. D. Davies, H. M. Tovmassian; M.N.R.A.S. 127, 45 (1963)
Get mass and density

W. E. Howard III, S. P. Maran; Ap. J. Supp. 10, 1 (1964)
#223 in list

W. W. Morgan, et al.; Ap. J. 142, 974 (1965)
Spectral classification of 17 stars in NGC 2244

W. G. Mathews; Ap. J. 144, 206 (1966)
Radio observation of a minimum in central region

N. H. Dieter; Ap. J. 150, 435 (1967)
Electron temp. from 158-alpha recombination line

W. M. Goss; Ap. J. Supp. 15, 131 (1967)
OH positions

J. A. de Boer, et al.; BAN 19, 460 (1968)
Electron temp. from 166-alpha recombination line

D. O. Edge, et al.; Mem. R.A.S. 68, 37 (1968)
Flux at 159 MHz

J. Meaburn; Astrop. and Space Sci 1, 230 (1968)
Photographs of Rosette in Hα, [OII] and [OIII]

M. E. Sim; Pub. Royal Ob., Edinburg 6, 181 (1968)
Finds one certain globule in NGC 2244

Smith; Astrop. and Space Sci. 1, 68 (1968)
Hα observations of rad. velocity

Anderson; Ap. J. 160, 507 (1970)
Reddening for two stars: HD46150 and HD46485

Dufour, Lee; Ap. J. 160, 357 (1970)
Reddening for Rosette determined from 10 cm and recombination lines

NGC 3031

(M 81)

R. Hanbury Brown, C. Hazard; Nature 172, 853 (1953)
Flux at 158.5 MHz

N. W. Boggess; P.A.S.P. 71, 534 (1959)
Optical Isophotes

G. de Vancouleurs; Ap. J. Supp. 5, 233 (1960)
Position, color and type of galaxy

D. S. Heeschen, C. M. Wade; A. J. 69, 277 (1964)
Flux at 750 and 1400 MHz

H. Arp; Science 148, 363 (1965)
Detection of faint luminous ring {see photos in Sky and Tel. 30, 141 (1965) and 35, 11 (1968) }

M. De Jong; Ap. J. 142, 1333 (1965)
Contours at 750 and 1410 MHz

NGC 2403

W. E. Howard III, S. P. Maran; Ap. J. Supp. 10, 1 (1965)
#258 in list

M. S. Roberts; I.A.U. Sym. #31, 189 (1967)
21 cm contour plots give ring distribution

G. A. Tammann, A. Sandage; Ap. J. 151, 825 (1968)
General investigation of NGC 2403

M. Guelin, L. Wellachew, Astron. and Astrop. 1, 10 (1969)
Ring pattern of Roberts (above) not found