RADIO OBSERVATIONS OF PLANETARY NEBULAE

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1. INTRODUCTION

A discussion of radio observations for the period up to 1979 forms part of the general review given at the 1979 IAU General Assembly by Terzian (1980) and I shall be concerned here mainly with later results. With the advent of improved radio telescopes and techniques, in particular the coming into full operation of the Very Large Array (VLA), there has been an increasing interest in compact and proto-planetary nebulae and I shall discuss these observations in a separate section of this review.

2. RADIO SURVEYS

The Parkes radiotelescope has been used to observe a further 167 nebulae at 5 GHz (Milne 1979) and 98 nebulae at 2.7 GHz (Milne & Webster 1979). Combined with earlier observations, reliable data on a total of 332 sources at 5 GHz and 144 sources at 2.7 GHz are available and have been used to derive extinction coefficients and distances for the majority of these objects. Calabratta (1982) has used the Molonglo telescope to observe 43 planetary nebulae at a frequency of 408 MHz, achieving a detection rate of 22%. He found no evidence for non-thermal emission. Mross, Weinberger and Hartl (1981), using the 100m Effelsberg telescope at 5 GHz, detected 19 out of 39 objects selected from the list of new planetary nebulae compiles by Weinberger (1977). Much of the motivation for radio surveys relates to their use in deriving radio distances. Maciel and Pottasch (1980) have discussed the errors in distance determinations resulting from an assumed constant ionised mass for nebulae which may in fact be ionisation bounded: they found that the use of an empirical mass-radius relation leads to more consistent distances and distributions of intrinsic size. Subsequently, Milne (1982) has shown that ionisation-bound nebulae might be expected to follow an $M \propto R^{3/2}$ mass-radius relation. As applied to the radio data, nebulae can be expected to fall into the optically-thick or optically-thin (to L_α) regime according as their radio surface brightness is greater or less than a certain critical value which, at a frequency

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of 5 GHz, corresponds to a brightness temperature of 22K. Disagreement concerning distance scales remains, however, Maciel & Pottasch deriving distances some 50% smaller than those quoted by Milne. The Westerbork telescope has been used in an extensive programme of observations of planetary nebulae near the Galactic centre (Wenterloop & Dekker 1979; Isaacman 1980a/b, 1981; Isaacman, Wenterloop & Habing 1980) as part of a study of the mass distribution in the central parts of the Galaxy. These data are presented elsewhere in this Symposium and will not be discussed further here.

3. RADIO RECOMBINATION LINES

Walmsley, Churchwell & Terzian (1981) have reported measurements of radio recombination lines for six planetary nebulae and upper limits for a further three, extending earlier data to include low-frequency (2.37 GHz) and high-frequency (14.7 GHz) transitions. A non-LTE analysis produces electron temperatures substantially in agreement with those derived optically. The frequency dependence of the observed line/continuum ratio for NGC 7027 is best fitted by a model having an electron density of 5 x 10^4 cm^{-3}, although some discrepancies with the observations remain. Viner, Vallée & Hughes (1979) have fitted the radio continuum and recombination line emission from NGC 7027 with a series of models which incorporate power-law radial density variations and allow for nebular expansion. Although the continuum data can be fitted by a range of models, including one having uniform electron density, the recombination line data appear to require an $n_e \propto R^{-2}$ density gradient. It should be noted however that such a variation is unlikely to be compatible with the sharp outer boundary seen on radio continuum maps; it is also inconsistent with the theoretical model considered by Guiliani (1981) which predicts an increasing radial density gradient. Walmsley et al. (1980) have noted that the line intensities used by Viner et al. may be in error by up to 50% and further modelling should probably incorporate the results of recent radio continuum mapping.

4. RADIO MAPPING

Felli & Perinotto (1979) have used 5 GHz observations made with the Westerbork telescope (WSRT) to compare the radio and optical brightness distributions of 8 planetary nebulae. None showed any sign of the patchy extinction apparent in NGC 7027. The VLA has been used to map a number of 'classical' planetary nebulae and some of these results will be presented in the next contribution. Radio mapping at longer wavelengths is beyond the capability of current instruments due to the low surface brightness of the sources, although some lunar occultation observations have been made at 327 MHz (Gopal Krishna 1978). With the planned improvements in the sensitivity of existing telescopes such as the WSRT and the prospect of further measurements from the VLA it can be expected that more high quality radio maps will be appearing.

5. COMPACT AND PROTO-PLANETARY NEBULAE

Johnson, Balick & Thompson (1979), using part of the VLA at 4.9 GHz, successfully detected 8 out of 13 stellar planetary nebulae which were observed; these sources were resolved by the VLA and appeared to be moderately compact but comparatively distant nebulae. Kwok, Purton & Keenan (1981) list 40 planetary nebulae observed at the Algonquin Radio Observatory (ARO) at a frequency of 10.6 GHz. The majority were found to be optically thin above 5 GHz but six of the objects appeared to have a higher turn-over frequency and were subsequently observed with the VLA.

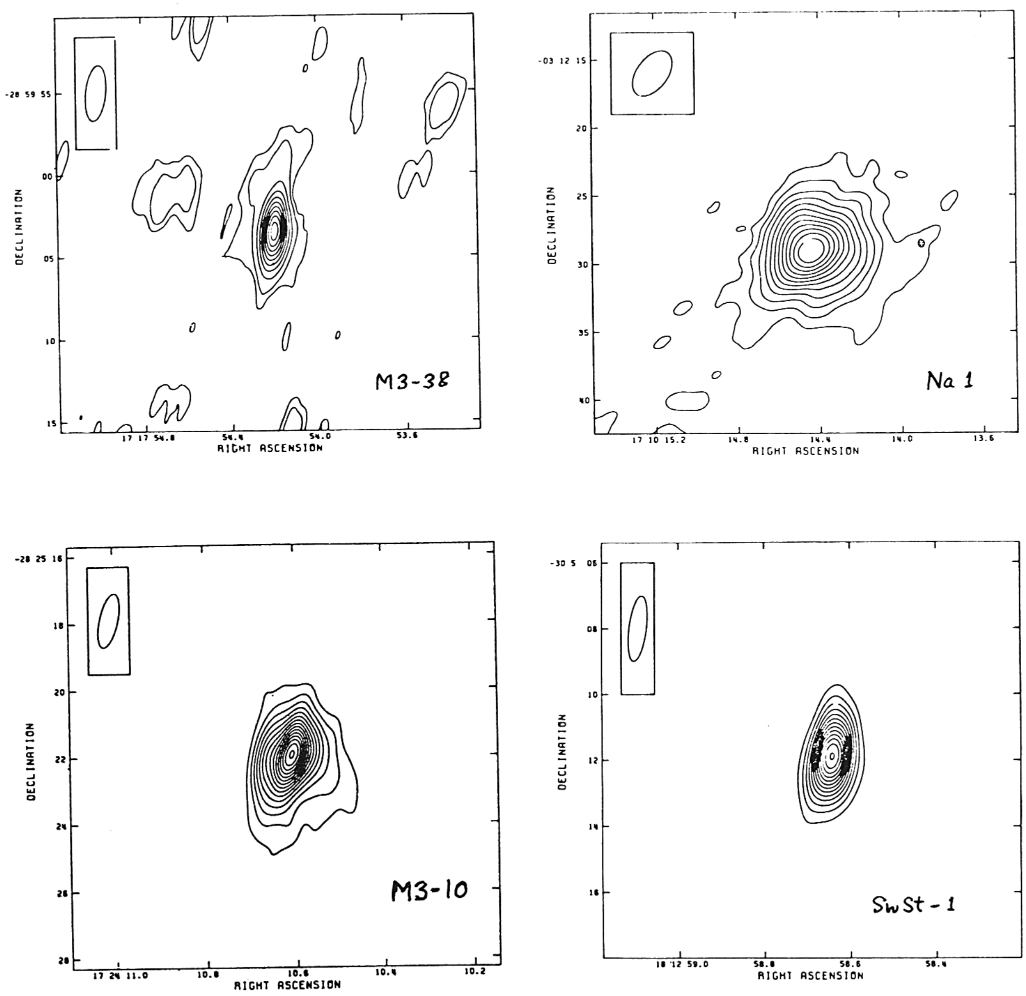

Figure 1. Maps of four compact planetary nebulae obtained with the VLA at 5 GHz. [From Kwok, Purton & Keenan (1981)]

Maps of the four of these sources which were detected by the VLA are shown in Figure 1. Two of the objects, M3-38 and SwSt-1, were found to have the high emission measures ($\gtrsim 10^8$ cm^{-6} pc) appropriate to young planetary nebulae. Purton et al. (1982) have recently reported a comprehensive series of observations of mainly emission-line objects but including a number of planetary and proto-planetary nebulae. 44 of the 325 objects studied were detected as radio sources, the probability of detection correlating strongly with the presence (optical) forbidden lines and, less strongly, with the existence of dust emission. Thirteen of the objects exhibited low frequency spectra approximating an $S \propto \nu$ law, consistent with mass outflow; this category included the suggested proto-planetaries HM Sge, V1016 and Hb 12. On the colliding stellar wind model proposed by Kwok, Purton & Fitzgerald (1978) this emission represents the ionisation of the original red giant stellar wind; the application of this model to the case of HM Sge has been discussed in detail by Kwok & Purton (1979) who find the model can explain satisfactorily the existing optical, infrared and radio data.

A particular property of some proto-planetary nebulae is the existence of radio variability on time scales of years or less. Much of this information derives from measurements carried out over a period of years at the Algonquin Observatory. The results for four sources are shown in Figure 2. In the case of GL 618, for which spectral information is also available, the changes are consistent with the progressive ionisation of an optically thick HII region (Kwok & Feldman 1981). It may be remarked in passing that the accurate flux measurements of weak sources can present observational uncertainties as is illustrated by the example of K648, below.

Frequency GHz	Flux density mJy	Reference
2.7	4.4)	Johnson 1976
8.1	3.3)	
4.9	16 ± 4	Johnson, Balick & Thompson 1979
10.6	16 ± 5	Kwok, Purton & Keenan 1981
5.0	9 ± 4	Mross, Weinberger & Hartl 1981
5.0	4.0 ± 1.7	Birkinshaw, Downes & Pooley 1981

Flux density measurements of the planetary nebula K648

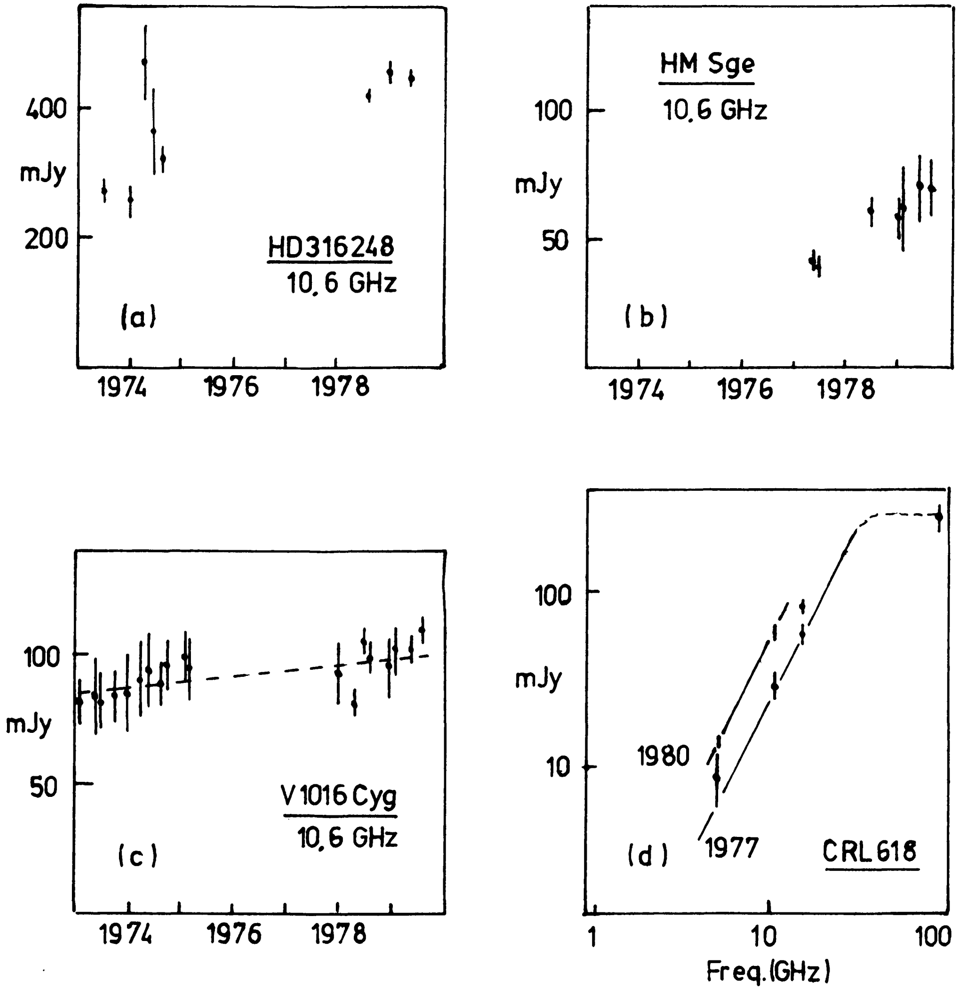

Figure 2. Flux density variations. [(a) (b) and (c) from Purton et al. 1982; (d) from Kwok & Feldman 1981]

6. CONCLUDING REMARKS

As mentioned earlier, much of the recent progress has been concerned with proto-planetary objects and it is clear that a distinct class of object has been identified. The link between these objects and the 'classical' planetary nebulae is perhaps less well proven. Infrared studies (Aitken, Roche, Spenser & Jones 1979) have found silicate emission features in proto-planetary objects but not in other planetaries, such as the compact nebulae NGC 7027 and BD 30°3639. There is considerable evidence supporting a binary interpretation for

V1016 and HM Sge (Pazcynski & Rudak 1980; Thronson & Harvey 1981) whereas a relatively small proportion of planetary nebulae are known to comprise binary systems. An interesting test of the colliding stellar wind model (Kwok et al. 1978) will be provided by the evolution of the radio spectrum of HM Sge, where, as noted by Kwok & Purton (1979), one would expect to see the emergence of an $S \propto \nu^2$ spectrum. The spectral dependence of flux variability in this and other sources will clearly provide useful data for models of nebular evolution.

Although not mentioned previously in this review, current advances in millimetre and sub-millimetre telescopes and receivers should allow the detection of neutral material associated with planetary nebulae to be extended to the more compact nebulae and help to elucidate their dynamics and origin. The first detection of HI associated with a planetary nebula, reported in a poster contribution to this Symposium (Rodriguez & Moran) illustrates one of the possibilities opened up by the availability of improved angular resolution. As in other areas of astrophysics, future advances are likely to result from a synthesis of observational data from many different parts of the spectrum and the improvement in radio techniques should ensure that radio observations continue to play an important part.

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OSTERBROCK: Is it possible, from radio measurements, to fairly unambiguously identify "new" (previously uncatalogued) PN? Would it be possible, by a radio survey, to find all planetary nebulae within, say, 2 kpc of the Sun, eliminating extinction effects of interstellar dust?

SCOTT: This would require high resolution surveys at two or three frequencies to pick out the thermal sources. The problem would be to distinguish PN from compact H II regions (W3 (OH) and NGC 7027 are very similar in their radio properties).

ISAACMAN: The Westerbork search for Galactic centre PN was at $\lambda = 21$ cm and 6 cm and yielded only one unambiguous and one possible PN. Unless one has sufficient spatial resolution to resolve the shell, some kind of optical or infrared spectral information is required to distinguish PN from compact H II regions.

TERZIAN: Together with K. Turner at the Arecibo Observatory, I have just completed a radio interferometric survey at $\lambda = 12$ cm of compact PN. Analysis is in progress.

WADE: Which (the radio or the optical) values of electron temperature and density have changed in order to bring about the present "agreement" between radio and optical studies of PN?

TERZIAN: The radio values have changed through non-LTE analysis of the data. However, the optical results also change, depending on the observer! It is too early to say that there is reasonable agreement between radio and optical determinations of electron temperature and density.

SEATON: With regard to optical and radio observations, the radio recombination lines involve a transfer problem and hence probe in depth in a way which cannot be achieved by optical observations.

MALLIK: Could radio recombination line observations tell us something about electron temperature fluctuations in PN?

TERZIAN: Not as yet: we need radio recombination line measurements at high angular resolution. Perhaps the VLA will be used for such work.

FLOWER: IUE and optical observations of Sw St 1 and Hb 12, mentioned in Scott's talk, indicate electron densities of 10^5 cm^{-3} and 10^6 cm^{-3}, respectively. In the case of Sw St 1, the density is determined directly from high dispersion observations which resolve the C III λλ 1907, 1909 doublet.