HIGH RESOLUTION MAPS WITH THE VLA

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The Very Large Array is a radio picture making instrument operated by the National Radio Astronomy Observatory in Socorro, New Mexico. The array, which has been in full time operation for more than 2½ years, operates at four main wavelengths, 1.3, 2.0, 6.0 and 20 cm with achievable resolutions of .05, .08, .25 and 0.8 arc seconds respectively.

One of the first objects to be mapped (May 1977) with the VLA was the planetary nebula, NGC 40 (Hjellming, Bignell, Balick 1978). Since then there have been numerous VLA observations of different planetary nebulae (PN).

The classical planetaries are being mapped with the intention of learning more about the physical processes of the later stage evolution whereas the early evolution is being studied from high resolution and high sensitivity VLA maps of young planetaries. The latter class of objects is a sub-class of active Galactic objects consisting of symbiotic sources, cataclysmic binaries, novae and young planetary nebulae which are being studied extensively with the VLA. More fundamental problems such as distances to planetary nebulae are also being tackled. The current review is not aimed at presenting a complete list of all the available VLA observations of PN, but will be slanted towards summarizing some of the more interesting sources and recent results.

"CLASSICAL" PLANETARY NEBULAE

These PN are typically ≥0.5 arc minute (large) in diameter and have the optical appearance of a (modified) doughnut, shell or other peculiar structure (such as loops, etc). The radio spectrum of these objects is generally optically thin at wavelengths shorter than 20 cm.

D. R. Flower (ed.), Planetary Nebulae, 69–78.

NGC 6853

The Dumbbell nebula is a well known relatively close PN approximately 8 arc minutes in size. The nebular emission exhibits a moderate range of excitation with some stratification (Goudis et al 1978). One interesting feature is the enhancemnt of [NII] emission relative to Hα in the outer parts of the nebula (Hua and Louise 1981). There is also a secondary shell of optical emission from a region of about 15 arc minutes centered about the main nebula (Perek and Kohoutek 1967, Millikan 1974). The VLA radio maps (Bignell 1982) shown in Figure 1, indicate two characteristics. Firstly, the general radio features most closely resemble the Hα optical emission distribution with significant differences from the low and high excitation emissions, both of which differ significantly themselves. Secondly, there is no indication of radio emission from the secondary shell down to a low emission level.

NGC 6543

The PN, NGC 6543, has a striking optical appearance in that most photographs show a structure of two overlapping elliptical rings. This source has been mapped both in the radio from VLA observations and in selected optical lines using the Kitt Peak 4 and 2 meter telescopes by Balick et al 1982. The 20 and 6 cm data are presented in Figure 1. Although the gross features of the radio appear similar to those of most optical pictures, a comparison of the radio maps with optical line maps of different excitations reveals that the distribution in the lines of Hα, Hβ and the high excitation lines of [OIII] appear to resemble the radio emission approximately, wheras the distribution in low excitation lines of [NII] and [SII] differs substantially from the radio and shows very unusual structures some of which resemble a "string of pearls".

NGC 40

This is a moderately close PN approximately 40 arc seconds in size. Optical photographs show a bubble type morphology. The VLA maps (Balick et al 1982) at 6 and 20 cm show similar gross features to optical pictures. It is worth noting that the [OIII] line differs significantly from the radio whereas the low excitation line maps more closely resemble the radio emission. This trend is opposite to that found in NGC 6543. Both NGC 40 and NGC 6543 show different radio and optical correlations than NGC 6853! Since these nebulae are probably about the same age it would be interesting to know why the excitation structures relative to the radio distributions differ so much. Do these differences result from different evolving processes, environments, parent objects or some combination of these factors?

Further VLA observations of both NGC 6543 and NGC 40 will allow one to look for evidence of a circumstellar wind and any narrow region

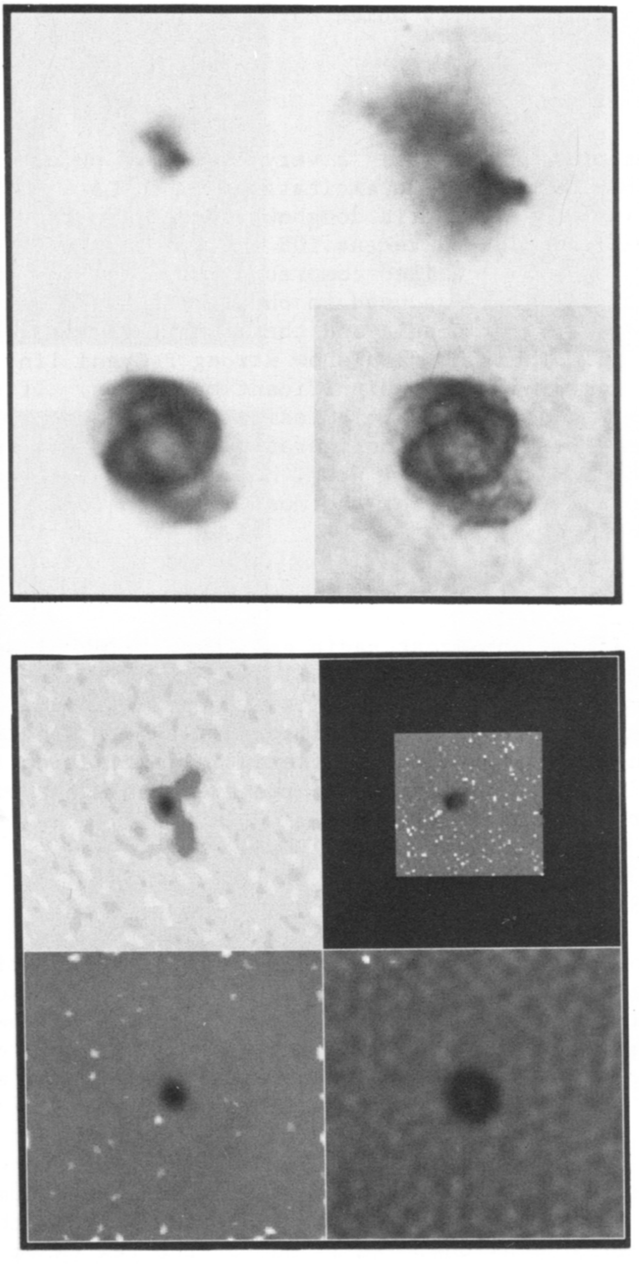

Figure 1. Top row: VLA images of NGC6853 at 20 cm (left) and 6 cm (right) from observations in D array. Second row: VLA images of NGC 6543 at 20 cm (left) and 6 cm (right) from observations in A array. Third row: VLA images of Hubble 12 at 6 cm (left) and 1.3 cm (right) from observations in the B and A arrays respectively. Bottom row: VLA images of VY2-2 at 6 cm (left) and 2 cm (right).

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at or near the nebular boundary which may show signs of anomolous spectral lines.

IC 3568

The "thereotician's" nebula is a very symmetric object about 8 arc seconds in diameter and of medium excitation. The VLA 6 cm map (Balick et al 1982) shows a very symmetric doughnut shape. Harrington and Feibelman (1982) have combined recent IUE and VLA observations with optical data to propose a detailed comprehensive model for this source. The low resolution VLA data was used to obtain the gas density distribution throughout the nebula and they find that the total mass of the nebula ~.005 Mo. Their UV data show strong P Cygni line profiles indicating a stellar wind with a significant mass loss. If this is the case there probably should be radio emission from the central star. The current VLA observations (A configuration) shows no strong evidence of radio emission from the central star, however, the observations are noise limited and the additions of the most recent B configuration should prove more informative.

NGC 7027

This is one of the strongest radio and IR emitting planetary nebulae. The VLA 6 cm map (Balick et al) shows that the nebula is about 12 arc seconds in size and exhibits a doughnut structure with two bright peaks in the ring which are consistent with a tilted cylinder geometry. Although there is strong differential extinction in the direction of NGC7027, deep optical pictures are consistent with the radio maps (Atherton et al 1979).

YOUNG PLANETARIES

The set of objects considered as young PN have observational properties strongly indicating significant mass loss. The sources tend to have strong IR emission and their radio spectra tend to be optically thick at wavelengths longer than 1 cm with spectral indices consistent with mass loss. Many of these sources are small in angular extent.

VY2-2

This is classified as a PN based on its optical spectrum. It is a strong IR source undergoing mass loss as indicated by both the IR and optically thick radio emissions. It is one of the few PN to exhibit molecular radio emission (Davis et al 1979). The OH emission properties of VY2-2 resemble some type II OH/IR stars and show a single asymmetric shape suggestive of an expanding shell in which emission from the shell on the reverse side of the nebula is absorbed by the PN. The 2 cm VLA map of Seaquist and Davis (1982) shows that the source is approximately 0.4 arc seconds in size and has the doughnut shape characteristic of many PN. It is interesting to note that the peak of

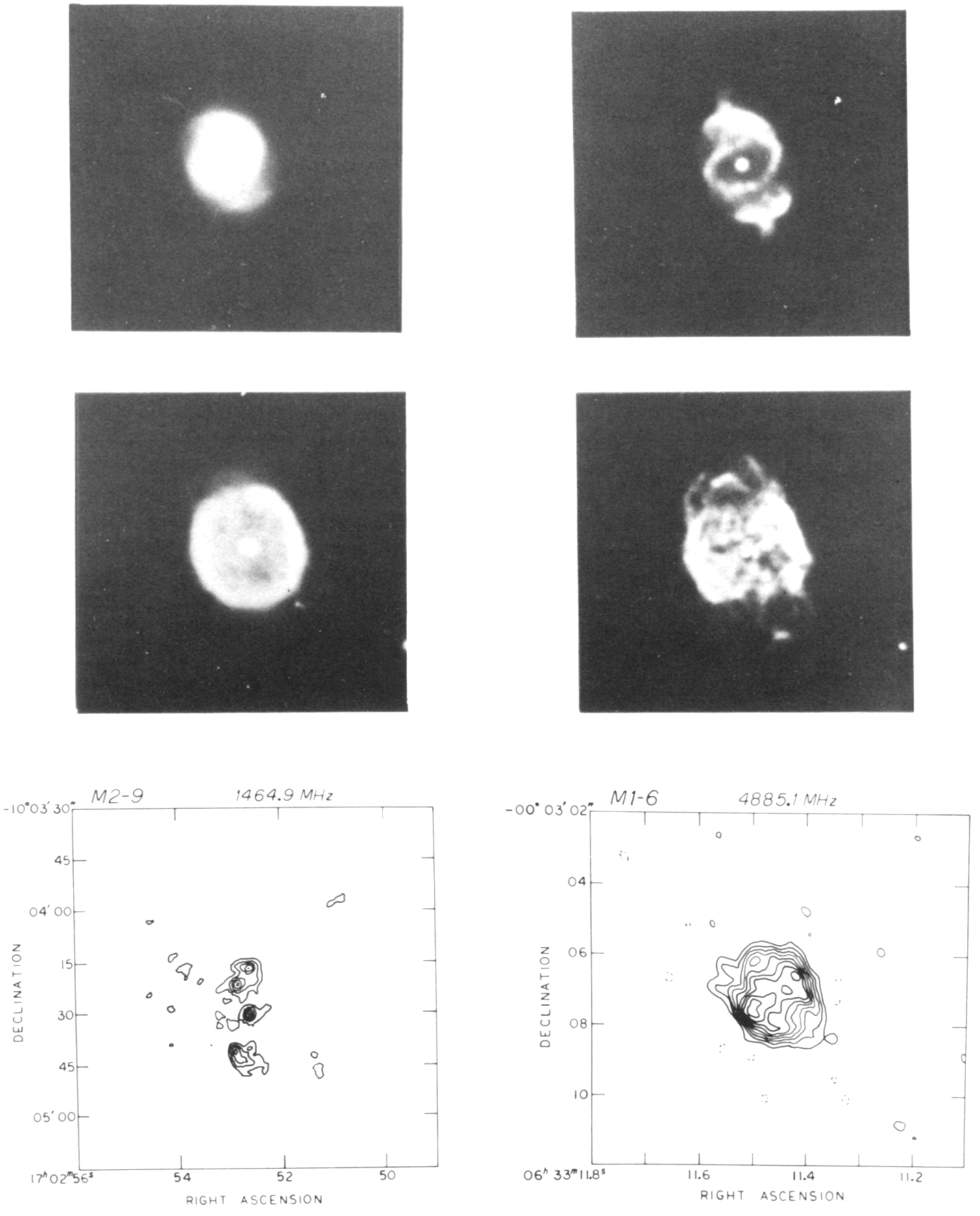

Figure 2. Top row: KPNO pictures of NGC 6543 in the λ5007Å [OIII] line (left) and λ6731Å [SII] line (right). Second row: KPNO pictures of NGC 40 in the λ5007Å [OIII] line (left) and λ6584Å [NII] line (right). Bottom row: VLA contour maps of M2-9 at 20 cm and M1-6 at 6 cm.

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the OH emission lies in the shell (Seaquist and Davis 1982) and not at the center of nebula! In addition to the ring there appears to be faint emission extending to the north which is most evident at 6 cm. What are the relationships of these observational features?

M2-9

This pretty bipolar nebular is about 40 arc seconds in size with a 13 magnitude central condensation (Calvet and Cohen 1982). The optical spectra suggest ionization stratification in the core with high electron densities and a different environment in the wings where [OI] densities greatly exceed the [NII] densities. The 20 cm and 6 cm VLA maps (Purton and Kwok 1982) show extended structure both north and south overlapping the bipolar structure seen optically. The radio core exhibits an optically thick spectrum at wavelengths longer than 1 cm whereas the wings are optically thin over most of the radio spectrum. The core is unresolved (<.1 arc second) at 1.3 cm. The radio properties of this nebula are consistent with the contact binary model proposed by Morris (1981) for the origin of bipolar nebulae (Purton and Kwok 1982).

Hubble 12

This nebula was classified by Perek and Kohoutek (1967) as a PN smaller than 10 arc seconds. The finding chart shows a stellar image. Its spectrum shows both forbidden and permitted lines. It is also a strong IR source. The VLA maps at 20 and 6 cm show a central unresolved object with wings extending outwards in the shape of a "V" with an overall extent of about 10 arc seconds (Newell 1981). The shape of these lobes is difficult to understand but may be related to the biconical flow model for bipolar nebula and motion through the interstellar medium. The high resolution VLA map at 1.3 cm (Newell and Hjellming 1982) indicate very interesting structure in the core. The central source has a scale size of several tenths of an arc second in the shape of a disc with very bright emission to one side. It should be pointed out that the radio wings are similar to those of the symbiotic star V1016 Cygni and the small scale structure of the core is similar to the symbiotic star RY Scuti. What gives rise to this core structure and what is its relation to the larger extended wings? The radio spectrum of the core is optically thick below 1 cm and the wings are optically thin over most of the spectrum.

M1-6

It has been suggested that this low excitation PN (Kondrat'eva 1979) is a young PN. The optical image in the PK catalogue (Perek and Kohoutek 1967) is stellar. The VLA map at 6 cm shows a "typical" looking planetary nebula in the shape of a 2 arc second ring with a bright spot on one side of the ring. Unlike VY2-2, M2-9 and Hubble 12 the decimeter radio spectrum of this object is optically thin. Although

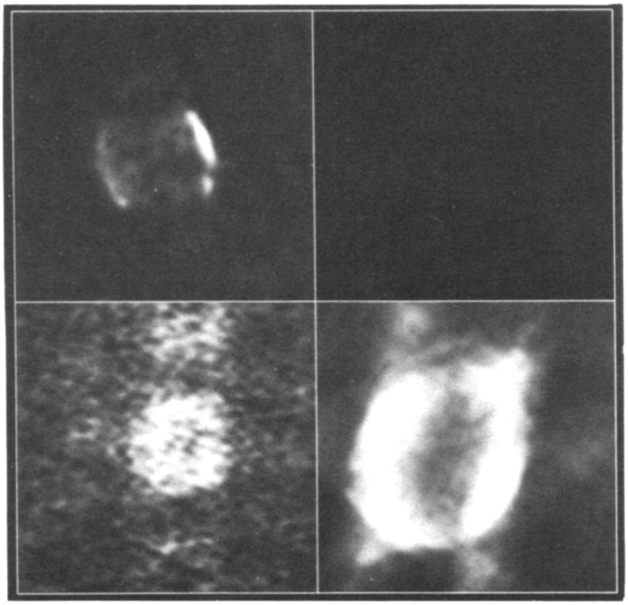

Figure 3. VLA images of NGC 40 at 20 cm (top Left), IC3568 at 6 cm (bottom left) and NGC7027 at 6 cm(bottom right). All observations we taken in A configuration.

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this PN maybe young there is no evidence in the radio spectrum of mass loss.

AFGL 618

This is a bipolar object with interesting IR, optical and radio properties. The radio source lies between the optical nebulosities and has CO emission lines resembling those found in circumstellar envelopes of early type stars. The radio spectrum, like VY2-2, M2-9 and Hubble 12, is optically thick below 1 cm but unlike these sources the spectral index is about 2 (cf .6 for the others) and is consistent with a black body spectrum (Kwok and Feldman 1981). The radio spectrum has shown variations over a three year period consistent with an expanding mass of ionized gas. The VLA 2 cm map shows a small source ≤ .3" in size coincident with the IR source and a 3" extension to the south-east. VLA observations at 1.3 cm indicate that the core consists of three components aligned approximately east-west and roughly coincident with the bipolar axis (Newell and Hjellming 1982). It has been suggested that this object may be undergoing the brief transition from a red giant to the young PN stage typified perhaps by M2-9.

RADIO EMISSION FROM CENTRAL STARS OF PLANETARY NEBULAE

The use of the VLA to map the classical planetary nebulae to very low brightness levels will not only help understand the evolution of the older PN but may also lead to the study of the link or connection between these and the young PN. Although early VLA observations with a small number of antennas (Thompson and Sinha 1980) of three classical PN showed no evidence of radio emission from the central stars, the more recent observations will extend the sensitivity of this study substantially and will include a larger number of more likely candidates.

SUMMARY

The above sample of sources, although not complete, does typify the recent research work carried with the VLA. The high resolution and high sensitivity of the VLA is currently being utilized to probe the cores of active objects such as symbiotic stars, novae and young planetary nebulae and through these studies more will be learned about the mechanisms responsible for the mass loss and early formation of the nebulae. Perhaps radio observations of this kind will also help lead to an understanding of the relationship or commonality, if any, between the different mass loss objects such as novae, red giant stars, young planetary nebulae, etc.

Finally, the VLA has and will continue to be used to study the radio spectrum and structure of small PN (Kwok et al. 1981, Issacman et al 1980, Johnson et al 1979) in an attempt to give more information on the physics of these objects, to identify PN and tackle more fundamental questions, such as envelope masses and distances to PN.

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SEATON: I think that one of the best ways of getting distances is from measured angular expansion rates. Perhaps ten or twenty years are required between first and second epoch "plates". What is being done about the first epoch?

BIGNELL: A VLA proposal has been submitted to obtain the first epoch maps of some dozen close PN.

REAY: Measurements of rates of angular expansion of PN must be supplemented by a good measurement of the expansion velocity in order to obtain a distance. The expansion velocity measured spectroscopically at the centre of the nebula may not be a good measure of the tangential velocity, which governs the angular expansion rate. Models for NGC 2392, for example, suggest that the tangential expansion velocity is 2 to 3 times less than the central (maximum) expansion velocity.

BIGNELL: Care will have to be exercised when choosing the radial velocity to be used in the determination of the distance. It may be necessary to map the radial velocity across the nebula.

SEATON: Overall expansion should be deducible from auto-correlation of first and second epoch observations. Comparison with Doppler velocities should give good distances.

CLEGG: Have you any preliminary results from your attempt to detect the central star of NGC 40?

BIGNELL: The data are only one week old and we do not yet have even a preliminary estimate.

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