THE ASTROPHYSICAL JOURNAL, 204:441–444, 1976 March 1

RADIO SYNTHESIS OBSERVATIONS OF PLANETARY NEBULAE. II. A SEARCH FOR SUB-ARCSECOND STRUCTURE

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Received 1975 April 21; revised 1975 August 20

ABSTRACT

Observations of 11 planetary nebulae with spatial resolutions from 0".2 to 2" at 2695 and 8085 MHz failed to show any very bright structure smaller than about 2". The observations are shown to be consistent with our present understanding of the temperatures and density distributions thought to typify most planetary nebulae.

Subject headings: nebulae: planetary — radio sources: general

I. INTRODUCTION

Probes of the sub-arcsecond structure of radio sources can now be made routinely using long-baseline interferometers. With the sensitivities which have become possible over the last few years, intriguing small-scale structures have been detected in both galactic and extragalactic objects. Miley *et al.* (1970) were the first to look for such structure in galactic planetary nebulae. Their reported detection of fringes in NGC 7027 came as a complete surprise because of the high brightness temperatures implied by the observations (perhaps as high as $10^{5.8}$ K). Miley *et al.* suggested at the time that the observed structure was inconsistent with the normal radio emission processes of a 10^4 K thermal gas; instead, the emission might arise from an extended envelope surrounding the hot (10^5 K) exciting star.

Since the observations of Miley *et al.* were performed, the radio link, the remote telescope surface and tracking limits, the receivers, and other IF processing equipment that they used have been replaced or improved. In addition, operation on three closely spaced and nearly colinear baselines between 33.2 and 35.2 km length at each of two polarizations (left and right circular) simultaneously at each of two frequencies (2695 and 8085 MHz) is now possible. The net increase in sensitivity can be as much as an order of magnitude when all baselines are combined. In 1974 November we undertook a survey in order to study the high-brightness core in NGC 7027 at two frequencies with better spatial resolution (0".2 at 8.1 GHz) and sensitivity, and to search for similar structure in 10 other planetary nebulae.

II. OBSERVATIONS AND RESULTS

The radio link interferometer consists of the standard NRAO interferometer made up of three 25 m telescopes on baselines as long as 2.7 km and a remote 14 m antenna situated 35 km southwest of the other telescopes. A brief description of the instrument and the major sources of errors has been presented by Balick and Brown (1974, 1975). To summarize briefly, the fringe separations vary between 0".2 and 2", depending on projected baseline length and frequency. The system sensitivity per baseline and polarization is of the order of 200 mJy in 30 s of integration, and the largest source of error, other than receiver noise, is atmospheric phase variations. After normalization to known calibration sources (observed every half hour), the repeatability is to within 10 percent for the fringe amplitudes, and $\sim 30°$ for the fringe phases. Such errors will not have appreciable effects on the results discussed below.

The observed sources and integration times are listed in Table 1. Observations of some nebulae, including NGC 7027, were repeated for consistency checks. In some cases observations of nearby sources were interspersed every 20 minutes in order to provide some coverage to the maximum number of potentially good candidate sources. In every case, observations were made with more or less uniform density over the full range of hour angle coverage afforded by the instrument. This, and the finite width of the so called "white-light lobe" of the 30 MHz bandwidth, mean that the field of view is restricted to values between 30" and 1', depending on the source-baseline geometry.

The nebulae observed, for the most part, are known to be small ($\theta \lesssim 30''$), and relatively bright radio sources for which radio fluxes and synthesis maps with $\sim 3''$ resolution were already available (Terzian *et al.* 1974, hereafter referred to as Paper I). FG Sge was included because of its possible classification as a young planetary nebula (Kraft 1974). Cohen and Barlow (1974) have observed a small-diameter infrared component coincident with the highly evolved nucleus of the planetary nebula A30. These latter two nebulae will be discussed separately below.

TABLE 1

OBSERVED SOURCES ON 35 KILOMETER BASELINE

PLANETARY NEBULA	RIGHT ASCENSION (1950)	DECLINATION (1950)	INTEGRATION TIME PER BASELINE (min)	FLUX (UPPER LIMIT) TO SUB-ARCSEC STRUCTURE (mJy)	
				2695 MHz	8085 MHz
IC 418...........	$05^h25^m09^s.31$	$-12°44'15''.0$	195	7	14
A 30.............	08 44 00.00	+18 04 00.0	360	9	11
NGC 6210.......	16 42 23.55	+23 53 29.1	160	14	18
NGC 6302........	17 10 21.31	−37 02 45.7	110	27*	33*
NGC 6572.......	18 09 40.60	+06 50 25.0	160	11	15
BD 30°3639.......	19 32 47.50	+30 24 20.6	225	12	13
FG Sge..........	20 09 41.00	+20 10 48.0	175	13	16
IC 4997..........	20 17 51.35	+16 34 23.0	230	10	12
NGC 7027.......	21 05 09.50	+42 02 03.1	320	11	12
NGC 7354........	22 38 27.90	+61 01 28.0	250	8	12
NGC 7662........	23 23 29.20	+42 15 35.6	235	10	14

* Large fluxes observed primarily on severely foreshortened projected baseline.

An inspection of the calibrated data shows no clear patterns of fringe amplitudes or phases. A possible exception is NGC 7027, which exhibits marginally nonrandom phase patterns at 2695 MHz; however, the phases of NGC 7027 observed on nearby baselines or different polarizations are inconsistent with one another. Synthesis maps were constructed for the observed sources by a Fourier transform of the data (with each point weighted equally; these maps are an excellent means of "stacking" the data at each position). No evidence of small-diameter components was seen, even for NGC 7027. The peak-to-peak noise found on the maps at 2.7 and 8.1 GHz is listed in Table 1.

Lower resolution maps (synthesized beam sizes of 3″ and 10″ at λλ3.7 and 11.1 cm, respectively) made from the standard three-element interferometer baselines were entirely consistent with those available synthesis maps previously published (Paper I). The nucleus of A30 was not detected to a 3 σ limit of 5 mJy. The λ11 cm map of FG Sge shows evidence of a weak, nonuniform ring of emission centered on the optical position much like the structure observed in other planetary nebulae. The diameter of the ring appears to be ~20″, with brightest components to the north and south. Since FG Sge is resolved at λ11 cm, only a lower limit of 20 mJy to its flux can be given. Additional observations on other baselines are needed of this interesting object in order to determine more accurate fluxes and structure.

III. DISCUSSION

We now explore the compatibility of these radio observations with optical photographs of planetary nebulae which often show considerable structure on a scale of a few seconds. Photographs of most planetary nebulae show large numbers of very small components as well as sharp edges in their macroscopic distribution, and it is not at all obvious why no signals are detectable on the present 35 km baseline interferometer, especially for lobe separations between 0″.6 and 1″, as obtained at 2.7 GHz.

The response of the interferometer is given by the Fourier transform of the source brightness distribution $\boldsymbol{B}(x, y)$, called the visibility function $V(u, v)$. Here (x, y) are a set of Cartesian coordinates on the sky centered at the "phase reference position," and (u, v) are the east-west and north-south Cartesian coordinates of the synthesized aperture. The relationship of the visibility function V to the fringe amplitude A (measured in janskys), the fringe phase ϕ, and the brightness distribution $\boldsymbol{B}$ is given by

$$V(u, v) \equiv A(u, v) \exp [i\phi(u, v)]$$

$$= \int_{-\infty}^{\infty} \int \boldsymbol{B}(x, y) \exp [2\pi i(ux + vy)]\, dxdy\,. \quad (1)$$

$V(u, v)$ has the property that $V(0, 0) = S_\nu$, the total flux of the source at frequency ν. At any given baseline projection (u, v), the interferometer response is proportional to a certain Fourier component of the structure in a particular direction. Speaking very crudely, the instrument responds best to isolated components whose sizes are smaller than the instantaneous separation between lobes.

Although many small components of size ~1″ (i.e., "clumps") are seen optically in planetary nebulae, it is not necessarily true that these will dominate the response of the interferometer at lobe separations of ~1″. That is, $V(u, v)$ is formed by taking the *complex* sum of the visibilities of each clump, and because of the complex exponential $\exp [2\pi i(ux + vy)]$, the magnitude of the total complex visibility will be considerably less than the sum of the individual visibility magnitudes. For N clumps of combined flux S_ν distributed randomly within a region larger than the lobe separation, the fringe amplitude approaches $S_\nu/\sqrt{N}$ for large N. For many clumps whose individual radio fluxes are small, the total complex visibility will be very weak and far below the noise level of the present instrument.

Rather than the individual clumps, it is the macroscopic distribution of the clumps which can be expected to dominate the instrumental response.

TABLE 2

VISIBILITY OF TWO-DIMENSIONAL MODEL BRIGHTNESS DISTRIBUTIONS WITH CIRCULAR SYMMETRY

Parameter	Gaussian Model	Disk Model	"Shotglass" Model	Thin-Ring Model
$T_b(\theta)$*	$T_b \exp[-4 \ln 2(\theta/\theta_H)^2]$	$T_b = 1(\theta \leq \frac{1}{2}\theta_H)$ $= 0\ (\theta > \frac{1}{2}\theta_H)$	$T_b = 2\theta_H/[(\frac{1}{2}\theta_H)^2 - \theta^2]^{-1/2}$ $(\theta \leq \frac{1}{2}\theta_H)$ $= 0$ $(\theta > \frac{1}{2}\theta_H)$	$T_b\delta(\theta - \frac{1}{2}\theta_H)$†
S_ν..................	$(2k/\lambda^2)T_b(\pi/4 \ln 2)\theta_H^2$ $(\mathrm{Jy}/1360)(\lambda/\mathrm{cm})^{-2}(T_b/K)$ $\times (\theta_H/\mathrm{arcsec})^2$	$(2k/\lambda^2)T_b\frac{1}{4}\pi\theta_H^2$ $(\mathrm{Jy}/1961)(\lambda/\mathrm{cm})^{-2}$ $\times (T_b/K)$ $\times (\theta_H/\mathrm{arcsec})^2$	$(2k/\lambda^2)T_b\frac{1}{2}\pi\theta_H^2$ $(\mathrm{Jy}/981)(\lambda/\mathrm{cm})^{-2}(T_b/K)$ $(\theta_H/\mathrm{arcsec})^2$	$(2k/\lambda^2)T_b\pi\theta_H$ $420\,\mathrm{Jy}(\lambda/\mathrm{cm})^{-2}(T_b/K)$ $\times (\theta_H/\mathrm{arcsec})$
$V(w)$‡...............	$S_\nu \exp[-(\pi^2/4 \ln 2)(w\theta_H)^2]$	$S_\nu[2J_1(\pi w\theta_H)/\pi w\theta_H]$§	$S_\nu[\sin(\pi w\theta_H)]/\pi w\theta_H$	$S_\nu J_0(\pi w\theta_H)$
Envelope $[V(w)]$....... $w \to \infty$	$S_\nu \exp[-(\pi^2/4 \ln 2)(w\theta_H)^2]$	$S_\nu\pi^{-2}(2/w\theta_H)^{3/2}$§	$S_\nu(\pi w\theta_H)^{-1}$	$S_\nu\pi^{-1}(2/w\theta_H)^{1/2}$

$T_b = T_b(\theta = 0)$, θ_H = angular width [as defined by $T_b(\theta)$], θ = radial coordinate on the sky ($\theta = \sqrt{x^2 + y^2}$).

‡ w = radial coordinate in the (u, v) plane ($w = \sqrt{u^2 + v^2}$).

† T_b is defined by $T_b \equiv S_\nu[(2k/\lambda^2)\pi\theta_H]^{-1}$ and does not have its usual physical meaning.

§ A thick ring is the difference of an outer disk of flux $S_{\nu,0}$ and size θ_0 and an inner disk of flux $S_{\nu,i}$ and size θ_i, where $S_{\nu,0}/S_{\nu,i} = \theta_0^2/\theta_i^2$. For this model the visibility is given by $V(w) = 2[S_{\nu,0}J_1(\pi w\theta)/\pi w\theta_0 - S_{\nu,i}J_1(\pi w\theta_i)/\pi w\theta_i]$, where $S_\nu = S_{\nu,0} - S_{\nu,i}$. The envelope of $V(w)$ decreases as $w^{-3/2}$ for large w.

Distributions with sharp edges or other types of abrupt changes in $\boldsymbol{B}(x, y)$ will also have an appreciable value of $V(u, v)$, even for long baselines. This behavior is illustrated by various mathematical models $\boldsymbol{B}(x, y)$ shown in Table 2. These models are ordered by increasing first moment for $\boldsymbol{B}(x, y)$, and represent four plausible models for the gross brightness distribution of planetary nebulae, especially those for which $\boldsymbol{B}(x, y)$ has a strong minimum at the center of symmetry.

For the present observations the source size θ is $\sim 15''$, w is $\sim 3 \times 10^5\ \lambda$ at $\lambda 11$ cm, and $w\theta$ is ~ 20. The envelope of $\boldsymbol{V}(w)$ for large values of $w^2 = u^2 + v^2$ is shown in the bottom row of the table. For models of the brightness distribution which are strongly limb-brightened (i.e., have sharp edges), maximum values of the visibility function will be several percent of the total nebular flux. Total fluxes for these nebulae have been given in Paper I and are typically $\lesssim 1$ Jy. Thus the expected fringe amplitudes should be on the order of 0.05 S_ν or between 20 and 50 mJy for most nebulae, and 300 mJy for NGC 7027 if $V(w)$ falls off as $(w\theta)^{-\gamma}$, where $\gamma \lesssim 1$. The fact that no fringes were seen at this level probably implies that the visibility envelope falls off faster than $(w\theta)^{-1}$. Since most planetary nebulae appear as disks or thick rings, this result is certainly not surprising (see Table 2).

We note that it is easy to show from the formulae given in Table 2 that, even if weak fringes had been detected, it would have been easy to reconcile these observations with electron temperatures on the order of 15,000 K, provided the optical depth τ of the radio continuum is larger than about 0.1 and the emitting structure is distributed as implied by the radio-synthesis maps and optical photographs. Of course for values of τ exceeding unity, small-diameter bright components would probably be occulted by large opaque foreground material. For NGC 7027 and some of the other nebulae, the optical depth over parts (or all) of the nebula is undoubtedly quite large at 2.7 GHz, but generally less than unity at 8.1 GHz.

The quality of the Miley *et al.* data is sufficiently good that the existence of the hot core they report should not be dismissed lightly. It is conceivable, of course, that the core is variable in flux; this is conspicuously true for some various radio stars and X-ray sources. No evidence of a hot core has been seen subsequently in the center of NGC 7027 (Scott 1973; Paper I). Dr. Miley has kindly pointed out an analysis by Scott, who has shown that the results of Miley *et al.* can be reconciled with the source structure observed at 5 GHz on baselines shorter than $10^5\ \lambda$, and hence with emission from a thermal gas of temperature near 10^4 K. If this were the case, then variability would not be a likely possibility. We note that Scott's analysis relies on the assumption that the spatial structure does not change appreciably between 2.7 and 5 GHz, which is unlikely because of the rapid and differential changes in $e^{-\tau}$ over the nebula between these frequencies.

IV. SUMMARY

We have presented radio observations of planetary nebulae made with an interferometer whose lobe separations are between 0".2 and 2" at 2695 and 8085 MHz. None of the nebulae were seen to exhibit evidence of fine structure smaller than $\sim 2''$ and brighter than $\sim 15{,}000$ K.

The results of the present observations were shown to be consistent with the brightness distribution inferred from optical photographs. Individual "clumps" seen optically could not have been detected because of their intrinsically weak fluxes and properties of their macroscopic distribution. It appears that the visibility function of planetary nebulae falls off faster than the inverse of the projected baseline. This behavior is consistent with the appearance of these

nebulae seen in the optical photographs and radio-synthesis maps (as shown in Paper I).

Finally, the putative hot core reported by Miley *et al.* (1970) could not be detected in 1974 November.

It is a pleasure to thank Drs. E. B. Fomalont and G. K. Miley for useful discussions. The hospitality and assistance of the telescope operators and staff of the NRAO is greatly appreciated. B. B. was partially supported by NSF grant GP-39505X. This work was also supported by NAIC, which is operated by Cornell University under contract with the National Science Foundation. NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation.

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