Observations of NGC 7027 at 5 GHz

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The planetary nebula NGC 7027 has been mapped at 5 GHz with 6.5 arc sec resolution. The thermal nature of the continuum is confirmed and an electron temperature of 12 000 K ± 3000 K derived. It is shown that the absence of the H109α line reported by Terzian and Balick (1969) could be due to Stark broadening, which would imply electron densities \( \geq 2.7 \times 10^5 \) cm\(^{-3}\). From the shape of the radio spectrum it is deduced that the scale of the density fluctuations must be much smaller than the size of the nebula.

In spite of its fairly small angular size NGC 7027 has received a great deal of attention from astronomers. It has a very rich optical spectrum, extensively analysed by Aller (1954) and others, and has the highest emission measure of any known planetary nebula. Because of the high surface brightness of the nebula its radio and infrared emission have been much studied and, although the radio spectrum displays the characteristic features of thermal bremsstrahlung radiation, it differs from most other thermal sources in two respects: (i) its H109α recombination line is conspicuously absent (Terzian and Balick 1969) and (ii) it has a very strong infrared excess; at 20μ its flux density is two orders of magnitude higher than would be expected from thermal bremsstrahlung alone (Gillett et al. 1967). It is not yet established how many other planetary nebulae exhibit these two characteristics.

The small size of the nebula has hampered radio observations and, until now, it has not been possible to resolve the source at radio wavelengths. However the 5-GHz pencil beam of the Cambridge One-Mile Telescope is narrow enough to resolve NGC 7027 and in this paper the results of observations made with the telescope during the summer of 1969 are described.

Figure 1 shows the map of NGC 7027 at 4.995 GHz. At this frequency and declination the half-power beamwidths of the instrument are 6.5 arc sec in right ascension and 8.7 arc sec in declination. The map is derived from observations made with four aerial spacings, as described by Elsmore et al. (1966). The nebula has an integrated flux density of \( (6.7 \pm 0.7) \times 10^{-26} \) W m\(^{-2}\) Hz\(^{-1}\), in agreement with other determinations near this frequency (Hughes 1967, Davies 1968, Kaftan–Kassim 1969). The calibration source used was 3C 147 for which a flux density of \( 8.18 \times 10^{-26} \) W m\(^{-2}\) Hz\(^{-1}\) at 5 GHz was assumed (Kellermann et al. 1969).

FIG. 1. NGC 7027 at 4.995 GHz. The contour interval is 650 K and the cross represents the AGK2 position. The approximate disposition of the optical nebula is indicated by shading. The ellipse shows the half power beam of the telescope. Features at the level of the lowest contour are not necessarily significant.
Figure 2 shows the spectrum of the source derived from published values of flux density, with the present value included; the spectrum is that of a thermal source, optically thick below about 3 GHz.

The cross in Figure 1 is the AGK2 position of NGC 7027, which refers to the brightest part of the nebula, the peak of the north western condensation (Kohoutek, private communication). The approximate disposition of the rest of the nebula is indicated by the shading in Figure 1, based on Minkowski’s (1968) photographs taken with the 200-inch telescope in Hα light. No optical isophotes have been published but it can be seen that there is general agreement between the optical and radio maps. In particular the position angle of the major axis of the radio source is $120^\circ \pm 15^\circ$, in agreement with Curtis’s (1918) value of $135^\circ$.

To estimate the size of the radio emitting region its visibility function was examined at different hour angles and compared with that expected from some simple ellipsoidal models. Models in which the electron density has ellipsoidal symmetry are convenient because all the observed continuum radio properties are independent of any further assumptions about the distribution of gas along the line of sight within the nebula; in all ellipsoidal distributions neither the observed brightness dis-
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The distribution nor the shape of the radio spectrum (which is discussed below) depend on either the assumed diameter along the line of sight or the assumed orientation of the principal axes with respect to the line of sight.

Two models with ellipsoidal symmetry which fit the observed broadening in NGC 7027 equally well are as follows: (i) uniform electron density and projected diameters $9 \times 11$ arc sec; (ii) Gaussian density distribution with projected half-density diameters of $7 \times 9$ arc sec. In both of these models the half-widths of the brightness distribution increase with the optical depth through the centre; in determining the diameters allowance was made for the amount of self-absorption at 5 GHz indicated by the spectrum in Figure 2.

Many other density distributions would also produce maps resembling Figure 1, but the sharpness of the low frequency cut-off in the observed spectrum (Figure 2) puts a severe restriction on the possible models, in that those with a wide variation of emission measure will produce a more gradual change of slope that is observed. Thus, for example, the dotted line in Figure 2 is the computed spectrum for a model consisting of an ellipsoid with a Gaussian density distribution. The agreement between it and the experimental points is poor and cannot be significantly improved by altering the physical parameters of the model, such as electron temperature or central density. However, a model comprising an ellipsoid of gas of uniform density with an electron temperature of 12 000 K and a central emission measure of $7.8 \times 10^7$ pc cm$^{-6}$ produces a spectrum very close to the experimental points (the solid line). Assuming that the nebula is at a distance of 1.77 kpc (O'Dell 1962) its mean observed physical diameter is 0.083 pc; if this value is taken for its line of sight diameter an r.m.s. electron density of $3 \times 10^4$ cm$^{-3}$ is obtained.

The electron temperature and the emission measure obtained here depend strongly on the details of the model used and the diameter measured. Their accuracy is therefore probably no better than 25 per cent. The electron temperature is in reasonable agreement with the value of 14 000 K determined by Aller and Minkowski (1956) from forbidden line measurements. It is rather lower than Seaton's (1960) value of 17 000 K, also from forbidden lines, but given the simplicity of the model the discrepancy is probably not significant. In view of the unusual features of NGC 7027 mentioned in the first paragraph, however, it is important that the present observations have confirmed that the size of the radio source is compatible with the assumption that most, at least, of the radio emission is of thermal origin.

As stated above, the constant-density ellipsoid was chosen as a basis for calculating physical parameters because models with a varying density distribution, such as the Gaussian model, have a more gradual turn-over in the radio spectrum at low frequencies than is observed. Minkowski's photographs (1968) indicate, however, that the nebula has an irregular, filamentary character and Aller (1954) found spectroscopic evidence for emission from regions with electron densities ranging from $10^4$ to $2 \times 10^5$ cm$^{-3}$. Such a wide range in density can be reconciled with the sharpness of the low frequency cut-off if the scale of the density fluctuations is much less than the size of the nebula, so that a typical line of sight intersects ten or more filaments. Under these circumstances the emission measure, which is proportional to the mean square density along a path through the nebula, has a much lower dispersion than the electron density itself.

The range of surface brightness indicated by Minkowski's photographs implies a wide variation of emission measure. In the absence of photometric data it is not possible to determine whether this variation is compatible with the sharpness of the low frequency cut-off in the radio spectrum, or whether it is necessary to conclude that part of the variation in surface brightness is due to dust, the presence of which has been postulated by Krishna Swamy and O'Dell (1968) to explain the infrared spectrum. Optical isophotes would clearly be of great value here.

The fact that there are filaments in the nebula may account for the absence of the H109 line, since at high densities the effect of Stark broadening of the line by electron collisions must be taken into account. According to the calculations of Griem (1967) an electron density of $2.7 \times 10^6$ cm$^{-3}$ would broaden the H109 line to a width of 2 MHz, placing it below the limit of detection of Terzian and Balick (1969). Goldberg's (1970) suggestion that the absence of the line is due to self-absorption is unacceptable because it implies an optical depth of greater than 2.1 at 5 GHz, which is at variance with the observed radio spectrum of the nebula (Figure 2). In addition the electron density required by Goldberg is considerably higher ($> 10^6$ cm$^{-3}$) than is sufficient to produce the amount of Stark broadening required by the observations. Since Stark broadening is less

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important at high frequencies, searches for recombination lines with lower principal quantum number should confirm whether or not this is the correct explanation for the absence of the H109a line, although recent observations of recombination lines in diffuse H II regions by R. D. Davies (private communication) have cast doubt on the validity of Griem’s calculations in some circumstances.

Although the nebula is smaller than most of the planetary for which optical isophotes have been published, quantitative knowledge of the brightness distribution over the nebula would, when combined with the radio data, provide very useful information about the extent to which the gas is contained in knots and filaments. Such information would in its turn lead to a better understanding of the physical processes in planetary nebulae in general and NGC 7027 in particular.

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REFERENCES


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Miley et al. (Astrophys. Letters 6, 17, 1970) have recently reported the existence of a small, apparently non-thermal component in NGC 7027 with a flux density of $0.23 \times 10^{-14}$ W m$^{-2}$ Hz$^{-1}$ at 2.7 GHz. This discovery, though unexpected, is not in conflict with the conclusions of this paper since the component almost certainly contributes less than 10 per cent of the flux density at 5 GHz.