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FINE STRUCTURE IN NGC 7027

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ABSTRACT

Synthesis observations at 8085 MHz with spatial resolution of $\sim 2''$ show the distribution of radio emission from the nebula NGC 7027 to be complex. Main components separated by $\sim 5''$ are superposed on a broader background of radius less than $\sim 7''$. There is a general, but not detailed, agreement between radio and optical features of the nebula. Consequences of the radio and optical brightness distributions and radio optical depth are discussed.

Subject headings: nebulae, individual — planetary nebulae — radio sources

I. INTRODUCTION

NGC 7027 is a bright, well-studied nebula rich in astrophysical phenomena. Morphologically the nebula most resembles planetary nebulae; nonetheless, NGC 7027 exhibits a large number of characteristics which make it outstanding among all planetary nebulae. These include (1) an optical image much more asymmetric and featureless than most planetary nebulae, (2) an optical line spectrum which shows the largest range of excitations of any galactic nebula (Aller 1954), (3) an anomalous, completely obscured source of excitation whose effective temperature is at least $10^{5°}$ K (Miller and Mathews 1972), (4) a large infrared excess between 3 and 13μ (Gillett, Low, and Stein 1967; Willner, Becklin, and Visvanathan 1973), and (5) a dominant emission measure E, electron density N_e, and temperature T_e, larger than any other carefully studied planetary nebula (cf. Terzian and Balick 1972 and references cited within; also Goad, Goldberg, and Greenstein 1972). In addition, a radio source of brightness temperature greater than $\sim 10^{5.8°}$ K embedded within the nebula has been observed by Miley, Webster, and Fullmer (1970).

Optical photographs of NGC 7027 are shown in figure 1 (plate L7). The nebular extent seen on these exposures is of order 10″ (longer exposures show emission over a region $18'' \times 11''$). Within the central regions there exists brighter structure of a few seconds scale size. Radio synthesis observations at 11 cm (Webster, Wink, and Altenhoff 1970) and 6 cm (Wynn-Williams 1970) have shown that most, if not all, of the radio emission arises within structures smaller than or comparable to their beam sizes ($\sim 7''$). Unfortunately their angular resolution was not sufficient to study the smaller scale size structure seen optically (baselines $\lesssim 30{,}000\ \lambda$).

We wish to report here radio synthesis observations of NGC 7027 on baselines extending to 73,000 λ. The three element interferometer of the National Radio Astronomy Observatory (NRAO) was used at 8085 MHz. The corresponding angular resolution is $\sim 2''$. Simultaneous observations at 2695 MHz are also reported.

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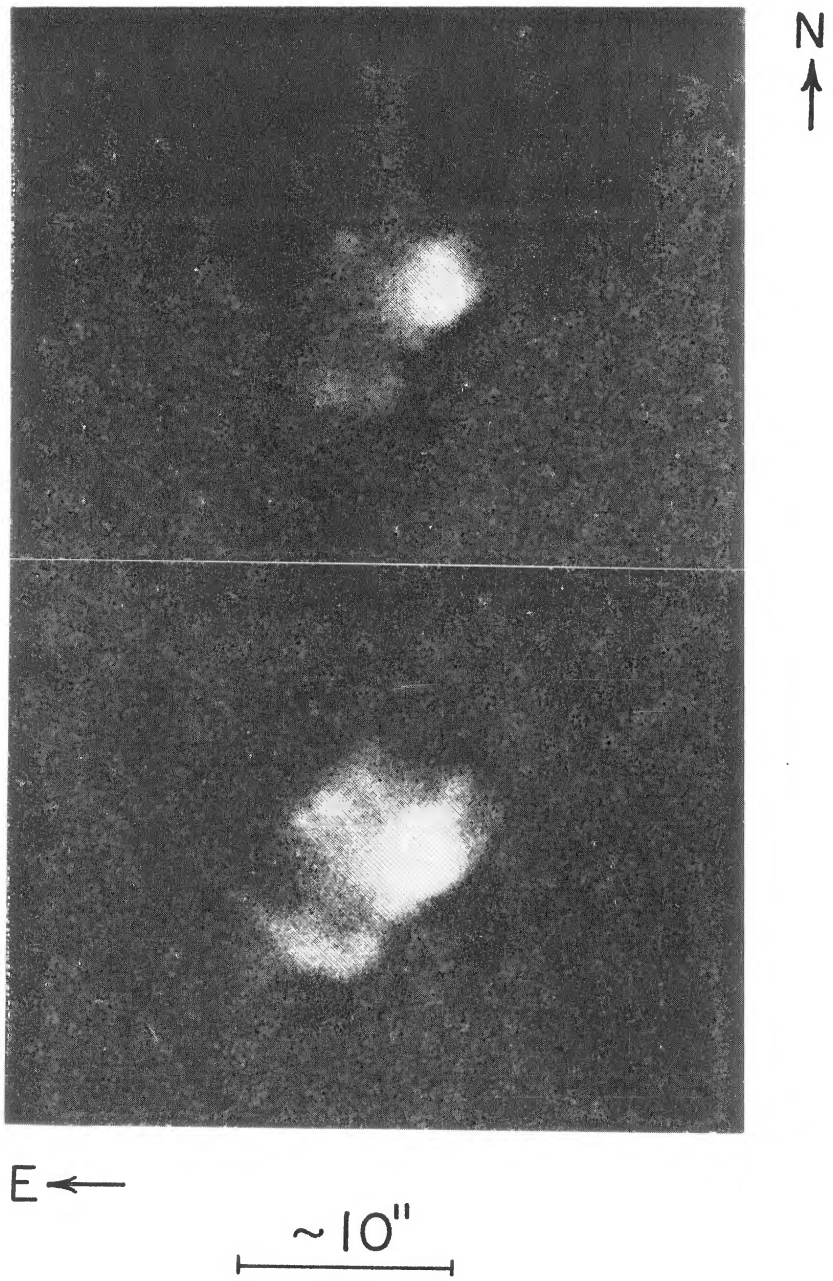

FIG. 1.—Two short exposures of NGC 7027. Both were taken in Hα light by Minkowski using the 200-inch (508-cm) telescope at Mount Palomar (from Aller and Liller 1968, and used with permission from University of Chicago Press). Photographs compare well with the drawing made by Curtis (1918).

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II. RESULTS

The synthesis maps of NGC 7027 are shown in figure 2. These were obtained from observations on collinear baselines with telescope separations between 300 and 2700 m in 300-m intervals. In addition, 800- and 1900-m separations were used. The observing technique and data reduction will be described elsewhere. At 8085 MHz the synthesized beam has half-power dimensions of $1''.8 \times 3''.0$. The beam at 2695 MHz is a factor of 3 larger in all dimensions.

The 8085 MHz map shows clearly that the source is complex. The separation between main components is $\sim 5''$, and these are superposed on a broader background containing most of the radio flux at this frequency. Further analysis of the source structure is continuing and will be reported later. However, the analysis presently completed clearly indicates that, after correction for sidelobes, the brightness distribution retains the general features described above, and any emission arising beyond a

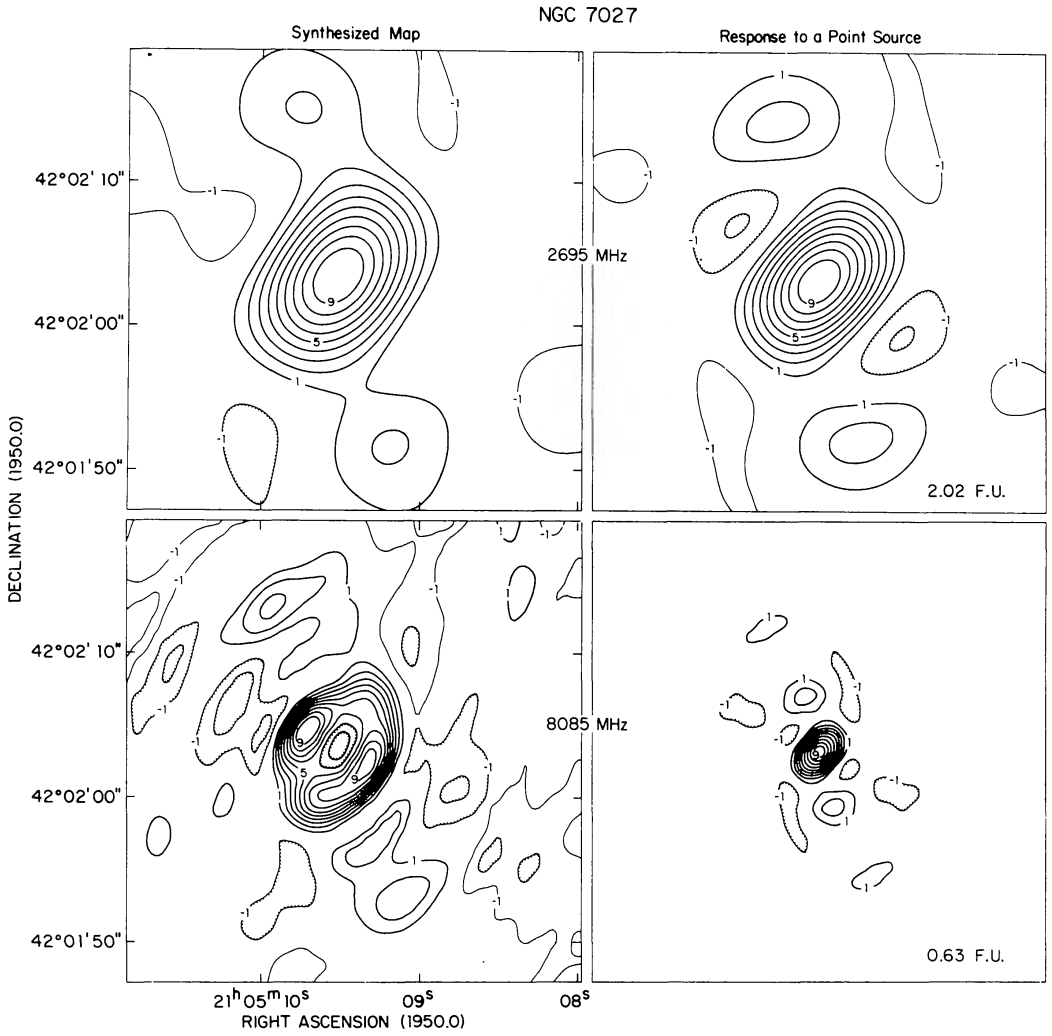

FIG. 2.—Synthesized maps and beams of NGC 7027 at 2695 and 8085 MHz. Contour levels are the same for the map and beam at each frequency. The brightness temperatures can be estimated from the flux of a model point source with the same peak brightness (fluxes of the model point source are shown with each beam pattern). From this we estimate that the contour levels are separated by approximately 680° and 220° K at 2695 and 8085 MHz, respectively.

distance of $\sim 7''$ from the source center has a brightness less than 5 percent of the maximum brightness.

The exact relationship between the optical and radio features is difficult to determine because of inaccurate optical positions and size scales. Kohoutek, in a private communication cited by Wynn-Williams (1970), has noted that the AGK 2 position of NGC 7027 corresponds to the bright optical feature in the northwest portion of the nebula (see fig. 1). This position is very nearly coincident with the western component in the 3.7-cm map. Assuming this to be the case, then the eastern radio component may coincide with the lower-brightness optical feature east of the major component. There is only a weak correlation between the southern optical extension and radio features. At the center of the radio map is a relative minimum in the brightness which is not reflected in the optical image of the nebula.

Additional synthesis maps were constructed from a subset of the data at 2695 and 8085 MHz for which the projected baselines (measured in wavelengths) are identical. This technique removes sampling biases between the maps, and is useful for studying the spectral behavior of the emission. Interestingly, these maps appear nearly identical at both frequencies except that the brightness of the 8085-MHz map is larger by a factor of 1.8; this same factor is also the ratio of flux densities found at 8085 and 2695 MHz (6.0 and 3.3×10^{-26} W m^{-2} Hz^{-1}, respectively). Consequently, the optical depth at 11 cm, τ_{11}, is nearly 2 (averaged over the $8''$ synthesized beam), and $\tau_{3.7} \sim 0.2$.

It then follows from the equation of transfer that changes in the 11-cm brightness distribution reflect changes of T_e in the gas which dominates the radio emission. On the other hand, the brightness is proportional to $E\ T_e^{-0.35}$ at 3.7 cm. Therefore, we feel that variations in the optical depth across the nebula are to be expected. In particular, the high-density emission regions which normally dominate recombination-line emission may well be optically thick at 6 cm. The negative results for the H109α recombination line (Terzian and Balick 1969) probably result from optical depth effects, as suggested by Goldberg (1970). High-resolution synthesis maps at about 5 GHz will be interesting in this regard.

III. CONCLUSIONS

The present observations show that the nebula NGC 7027 has a complex structure. There are at least two bright components surrounded by an extended envelope of radius $\sim 7''$. The westernmost component is very nearly coincident with the brightest optical feature and the anomalous high-brightness radio source reported by Miley *et al.* (1970). The other bright radio component lies near an optical feature of lesser prominence. There is little correlation between other radio and optical features.

It is interesting to note that the correspondence between optical and radio features in other planetaries is generally much better than in the case of NGC 7027 (high-resolution maps of other planetaries are in preparation and will be published in a more comprehensive report). We suggest, then, that the dissimilar radio and optical images of NGC 7027 might be explained by scattering of the optical emission in the large amount of local dust required to explain the infrared excess.

We also note that the radio image of NGC 7027 looks very similar to many other planetary nebulae observed with $\sim 2''$ spatial resolution. Insofar as these high-resolution radio-continuum observations can define a morphology, NGC 7027 is clearly a planetary nebula. Nonetheless, the question of nebular excitation bears further investigation. Observations of the high-brightness radio source on baselines of $10^6\ \lambda$ are planned for the near future.

Finally we mention that simple one-component models used to interpret previous radio observations are somewhat inappropriate, at least at frequencies greater than

$\sim$ 3 GHz. Larger values than $E \sim 10^{7.9}$ pc cm^{-6} and $N_e \sim 10^{4.5}$ cm^{-3} estimated from earlier observations (Webster *et al.* 1970; Wynn-Williams 1970) can be expected for the small-diameter bright structure. The physical conditions derived from studies of the radio recombination lines (Terzian and Balick 1972; Goad and Chaisson 1973; Bignell, in preparation) must also be carefully interpreted. Although estimates of the physical parameters from the lines are consistent with radio-continuum results, the agreement is probably fortuitous, since the line analysis makes the questionable assumption of local thermodynamic equilibrium throughout the emitting region.

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REFERENCES

Aller, L. H. 1954, *Ap. J.*, **120,** 401.
Aller, L. H., and Liller, W. 1968, in *Nebulae and Interstellar Matter,* ed. G. P. Kuiper and B. M. Middlehurst (Chicago: University of Chicago Press).
Bignell, C. 1973, in preparation.
Curtis, H. D. 1918, *Pub. Lick Obs.,* **13,** 57.
Gillett, F. C., Low, F. J., and Stein, W. A. 1967, *Ap. J.* (*Letters*), **149,** L97.
Goad, L. E., and Chaisson, E. 1973, to be published.
Goad, L. E., Goldberg, L., and Greenstein, J. L. 1972, *Ap. J.*, **175,** 117.
Goldberg, L. 1970, *Ap. Letters,* **5,** 131.
Miller, J. S., and Mathews, W. G. 1972, *Ap. J.*, **172,** 593.
Miley, G. K., Webster, W. J., and Fullmer, J. W. 1970, *Ap. Letters,* **6,** 17.
Terzian, Y., and Balick, B. 1969, *Ap. Letters,* **4,** 195.
———. 1972, *ibid.,* **10,** 41.
Webster, W. J., Wink, W. E., and Altenhoff, W. J. 1970, *Ap. Letters,* **7,** 47.
Willner, S. P., Becklin, E. E., and Visvanathan, N. 1972, *Ap. J.*, **175,** 699.
Wynn-Williams, C. G. 1970, *Ap. Letters,* **6,** 189.