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DISCOVERY OF RADIO BRIGHTENING IN AFGL 618

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ABSTRACT

Recent radio continuum observations of AFGL 618 have shown that the free-free emission flux density has increased by approximately a factor of 2 over a 2–3 yr interval, whereas the spectrum has remained optically thick up to at least 12 GHz. This is interpreted as the result of expansion of a compact H II region within the molecular/dust envelope of AFGL 618. The central star of the nebula is likely to be a 1 $M_\odot$ star now rapidly evolving into the planetary nebula stage.

Subject headings: infrared: sources — nebulae: planetary — nebulae: reflection — radio sources: general

I. INTRODUCTION

The infrared object AFGL 618 has excited considerable interest in recent years because of its unique optical-infrared-radio properties. It was discovered in the infrared sky survey of Walker and Price (1975), and the infrared source was found by Westbrook *et al.* (1975) to be located between two optical nebulosities. The CO emission line observed in AFGL 618 is wide ($\sim$ 40 km s^{-1}), resembling the CO profiles observed in circumstellar envelopes of late-type stars. The presence of an early-type central star inside the CO envelope has led to the suggestion that it is in transition between the red giant and planetary nebula stages (Zuckerman *et al.* 1976; Lo and Bechis 1976). Infrared emission lines of H_2 have been detected (Beckwith, Persson, and Gatley 1978; Thronson 1981), indicating the presence of expanding, shocked material. An optical brightening of 2 mag over a period of $\sim$ 30 yr is also noted by Gottlieb and Liller (1976). Radio continuum emission was detected by Wynn-Williams (1977) and is probably emitted by a dense, compact H II region inside the infrared source. In this *Letter*, we present evidence for an increase in radio flux from AFGL 618 between 1977 and 1980.

II. OBSERVATIONS

Radio continuum observations of AFGL 618 have been made at λ2.8 cm (center frequency 10.3–10.5 Ghz) at the Algonquin Radio Observatory (ARO)[1] since 1976 October (Feldman 1981). The beamwidth (FWHM) of the 46 m telescope is $\sim$ 2$'$.7 at this wavelength. Measurements were made by the method of "wagging," in which the source is observed alternately in each of the two antenna beams which are separated in azimuth by 8$'$.2.

Aperture synthesis observations of AFGL 618 were obtained at the Very Large Array (VLA)[2] on 1980 March 24. The observations were made using a subarray of up to 22 antennas at 4.885 GHz and up to 18 antennas at 15.035 GHz. The maximum baseline was $\sim$ 23 km, providing a resolution of $\sim$ 0$''$.5 and 0$''$.2 at 5 and 15 GHz, respectively. The source was observed three times at different hour angles at both frequencies. Standard NRAO calibrators were observed between on-source observations of $\sim$ 4 minutes' duration. The data were edited until satisfactory phase and amplitude closure on the calibrators were obtained. The calibrated visibility data were then transformed to a map, which was subjected to the "cleaning" process. The best-fit elliptical Gaussian components were then found, both from the cleaned map and in the transform domain using the calibrated visibility data. Flux densities, positions, and angular sizes were derived from the results of these fittings. Estimates of the flux densities were also obtained from the summation of the cleaned components. Since AFGL 618 is small in angular size, maps of low resolution were also made so that the integrated flux can be inferred from the peak flux values as well.

III. RESULTS

Figure 1 shows the radio spectra of AFGL 618 during epochs of 1977 and 1980. The upper spectrum includes data obtained at the VLA (1980 March) and ARO (1980 December). The lower spectrum is taken from Feldman (1981), which includes measurements between 1976 October and 1977 March. Optically thick blackbody curves (spectral index of 2.0) are also shown in Figure 1. We can see that the 1977 spectrum is consistent with an

[1] The Algonquin Radio Observatory is operated by the National Research Council of Canada, Ottawa, as a national radio astronomy facility.

[2] The Very Large Array of the National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

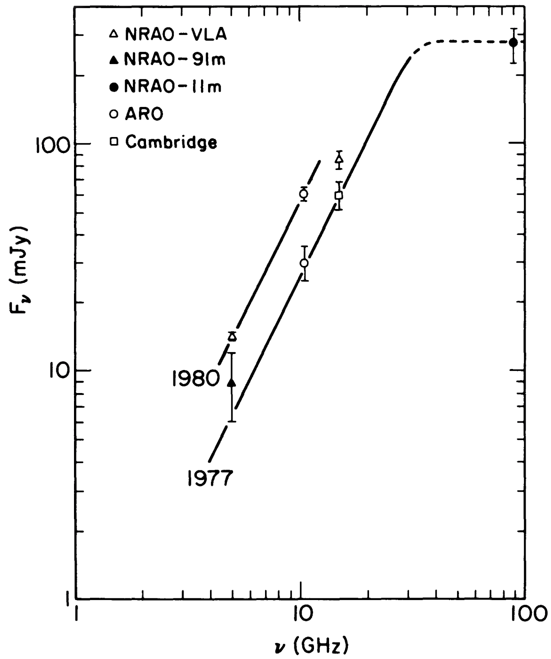

FIG. 1.—The radio continuum spectra of AFGL 618 in 1977 and 1980. The VLA data were obtained in 1980 March and the ARO point in 1980 December. The Cambridge point is taken from Wynn-Williams (1977) and details on the other 1977 data are given in Feldman (1981).

optically thick blackbody up to ~ 30 GHz, and radio emission from the object has definitely increased between 1977 and 1980. Another measurement at ARO in 1978 February shows a flux density similar to the 1977 January value shown in the figure. The earliest radio observation of the object is 6 ± 3 mJy at 5 GHz, obtained by Wynn-Williams (1977) who combined measurements made in 1973 September and 1974 June. This value is consistent with the 1976 October measurement by Gregory and Seaquist (see Feldman 1981) at 5 GHz using the NRAO 91 m telescope. However, the low signal-to-noise ratio of the 1973–1974 data makes it difficult to determine whether the brightening began in 1977–1978 or extends over a longer period to 1973.

The 1980 spectrum indicates that it may be optically thin at $\nu = 15$ GHz. However, a measurement at mm wavelengths is required to confirm this.

Low-resolution maps made at the VLA show that the area is clean over a 1′.5 × 1′.5 field around the infrared source with the exception of a confusing source of ~ 4 mJy (at 5 GHz) approximately 28″ northeast of the infrared source position. After a rough correction for the distance to the phase center, the flux density is estimated to be 5 ± 2 mJy. Because of higher noise levels, we are only able to put an upper limit of 30 mJy to the confusing source at 15 GHz. Assuming that it is an extragalactic source with a negative spectral index, then its flux density of 10.6 GHz would be negligible. However, the possibility that the single-dish measurements have been affected by this source cannot be excluded.

Figures 2*a* and 2*b* show the 5 and 15 GHz VLA maps of AFGL 618. A compact source of angular size ≲ 0″.3 is detected at the position of the infrared source (Westbrook *et al.* 1975; Wynn-Williams 1977). By fitting elliptical Gaussians to the calibrated visibility data, we determined the radio position (1950.0) to be

$$\alpha = 04^{h}39^{m}34^{s}.04 \pm 0^{s}.01; \qquad \delta = 36°01'16''.05 \pm 0''.02.$$

This coincides (within the errors) with the infrared position and is approximately midway between the two reflection nebulae. In the 15 GHz map (Fig. 2*b*) a tail of ~ 3″ in length extends eastward, probably as far as the eastern (and brighter) nebulosity. Although this tail is not seen in the 5 GHz map, the source is clearly elongated with a size of ~ 0″.7 in the EW and < 0″.3 in the NS. A bright knot can be seen on both maps at the far end of the 3″ tail. This confirms the suggestion by Westbrook *et al.* (1975) that leakage of starlight from a central star inside the IR object through the dust envelope is responsible for the illumination of the reflection nebula. The integrated flux density is 14.2 ± 0.5 mJy at 5 GHz and 85 ± 8 at 15 GHz.

IV. DISCUSSION

Temporal variations of thermal radio emission have only been detected in a few cosmic sources to date: the classical novae HR Del, FH Ser, and V1500 Cyg (Hjellming 1974) and the IR/emission line object HM Sge (Feldman, Kwok, and Purton 1979; Purton, Kwok, and Feldman 1981). The rise and decline of thermal radio emission in the case of novae can be understood as the result of the expansion of the nova ejecta (Seaquist and Palimaka 1977; Hjellming *et al.* 1979), although details of the nova envelope dynamics is yet to be understood. HM Sge has also been suggested to be a very slow nova (Paczyński and Rudak 1980; Kwok 1981).

The situation for AFGL 618 is quite different, however. Unlike HM Sge, no late-type spectral feature has been detected, and there is little evidence for a binary system. Although a gradual increase of visual brightness over 30 yr is noted (Gottlieb and Liller 1976), no optical outburst has been observed, as in the other four examples. The galactic location of AFGL 618 makes it unlikely to be a pre–main-sequence object. Given the high luminosity ($L \gtrsim 7.9 \times 10^3 D^2\ L_\odot$ [D in units of kpc], Kleinmann *et al.* 1978) and the presence of a thick circumstellar envelope, the only viable interpretation seems to be that AFGL 618 is in transition between the red giant and planetary nebula stages (Lo and Bechis 1976; Zuckerman *et al.* 1976).

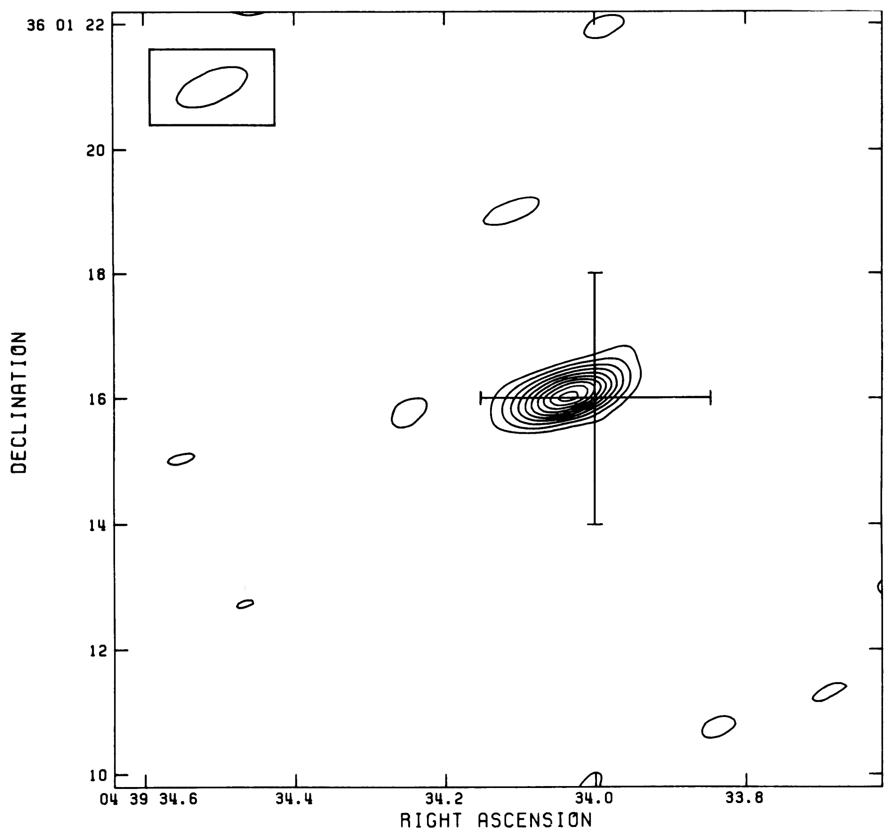

FIG. 2*a*

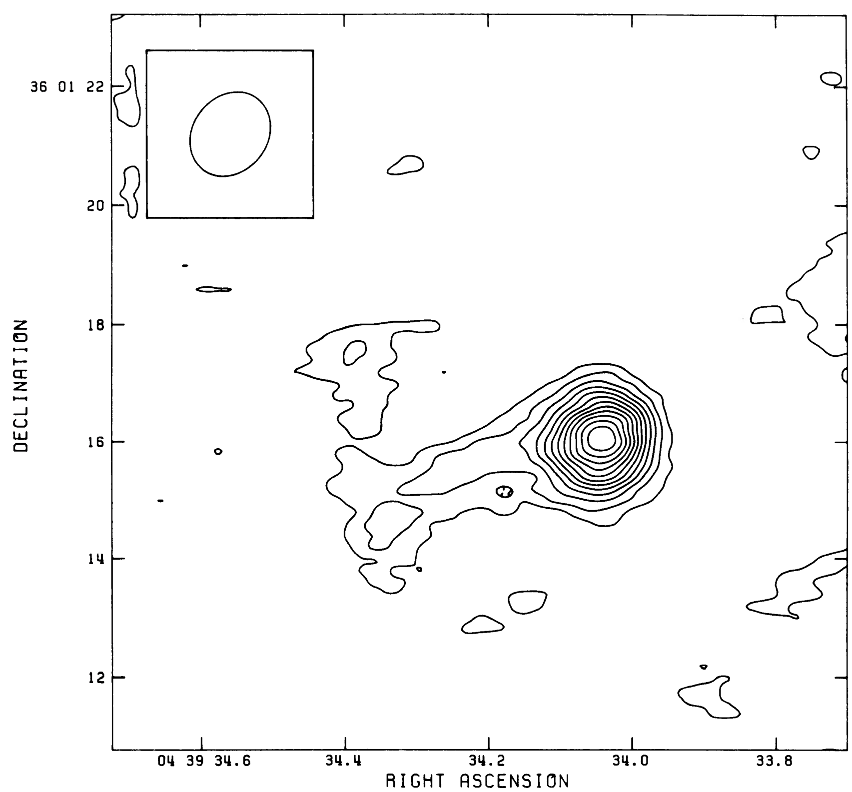

FIG. 2*b*

FIG. 2.—(*a*) The λ6 cm map of AFGL 618. The contour intervals are 1 mJy per beam area. The synthesized beam to the half-power is displayed at the corner of the map. The 10 μm infrared position (Wynn-Williams 1977) is marked with a cross. (*b*) The λ2 cm map of AFGL 618. The contour intervals are 5 mJy. The beam has been deliberately degraded by imposing a tapered function on the $u - v$ plane.

a) The Ionized Region

Figure 1 clearly shows that the current spectrum of AFGL 618 is optically thick at frequencies at least as high as 12 GHz. The spectral index is approximately +2, consistent with that expected for a uniform density H II region. The Cambridge 15 GHz result implies an angular size of 0″15 (assuming $T_e = 2 \times 10^4$ K, Westbrook *et al.* 1975) in 1977, whereas the 5 GHz VLA result implies a size of 0″22 in 1980. Because of the uncertainty in the start of the beginning of the radio brightening, the expansion velocity of the ionized region may range between 3 and $5 \times 10^{14} D$ cm yr^{-1}, depending on whether the radio flux densities remain constant between 1977 and 1978. An assumed distance of 2 kpc (Zuckerman, Terzian, and Silverglate 1980) leads to an expansion velocity of 220–330 km s^{-1}, much greater than the expansion velocity of ~ 20 km s^{-1} for the circumstellar molecular cloud (Lo and Bechis 1976) or typical expansion velocities of 20–50 km s^{-1} for planetary nebulae. An alternate explanation of the expansion of the H II region is that it is the result of the advance of an ionization front after an increase in the output of UV photons from the central star. For a uniform density medium, the time scale (t) of the expansion of the ionization front is $\sim [n_H \alpha^{(2)}]^{-1}$, where $\alpha^{(2)}$ is the recombination coefficient for all levels with $n > 2$ (Spitzer 1968). From optical emission line ratios, Westbrook *et al.* (1975) estimated the electron density to be as high as 10^5 cm^{-3}. Inserting this value into the above expression [with $\alpha^{(2)} = 1.46 \times 10^{-13}$ cm^3 s^{-1} for $T_e = 2 \times 10^4$ K] we get $t \sim 2$ yr, in order of magnitude agreement with the observed radio brightening time scale. The optical brightening time scale is longer (~ 30 yr^{-1}, Gottlieb and Liller 1976) because it is due to decreasing obscuration by the expanding dust envelope, which is expanding at only ~ 20 km s^{-1}.[3]

General physical conditions of the nebula can be estimated from the radio data. A turnover frequency > 12 GHz implies an emission measure ($\langle E \rangle_{\rm I}$, see Terzian and Dickey 1973) of $> 1.4 \times 10^9$ cm^{-6} pc (assuming 2×10^4 K). The lower limit of 90 mJy to the optically thin flux and the measured angular diameter of $< 0''.3$ can also be used to set another lower limit to the emission measure of 1980 ($\langle E \rangle_{\rm II} > 9.7 \times 10^8$ cm^{-6} pc). Using the optically thin flux density of 267 ± 45 mJy in 1977 with the corresponding angular size of 0″15, we derive $\langle E \rangle_{\rm II} \sim 1.5 \times 10^{10}$ cm^{-6} pc in 1977. These values are higher than the emission measure of any known planetary nebulae (Kwok, Purton, and Keenan 1981) and are consistent with the suggestion that it is an extremely young planetary nebula. The current ionized mass is $\sim 4/3\pi(\theta D)^3 \mu m_H n_H$, or $\sim 10^{-4} M_\odot$ assuming $\theta \sim 0''.22$, $D \sim 2$ kpc, and $n_H \sim 10^5$ cm^{-3}. Although this mass is low compared to known planetary nebula masses, it is expected to increase as more material is ionized by the central star.

[3] The 20 km s^{-1} is the measured gas velocity. Since the gas-dust drift velocity is < 20 km s^{-1} (Kwok 1975), the dust expansion velocity cannot be much larger.

b) The Central Star

The radio measurements can also be used to infer the nature of the embedded star. Since the turnover frequency is higher than 12 GHz and the optically thin flux density is currently > 90 mJy, $n_e^2 V$ of the H II region is found to be $> 4.7 \times 10^{58} D^2$ cm^{-1}. At a distance of 2 kpc, the spectral type of the embedded star must be earlier than B type. This is in agreement with the conclusion reached from the observed Hβ flux (Westbrook *et al.* 1975). This, coupled with the IR-derived luminosity of $7.9 \times 10^3 D^2 L_\odot$, puts the central star of AFGL 618 in the general location of young planetary nebulae in the H-R diagram. In order to maintain an H II region of the present size, a minimum of $4/3\pi\alpha^{(2)} n_H{}^2 \theta^3 D^3 \sim 2 \times 10^{35} n_H{}^2$ s^{-1} UV photons are required. Assuming $n_H \sim 10^5$ cm^{-3}, this required rate is easily satisfied by a planetary nebula nucleus in this part of the H-R diagram.

c) The Infrared Spectrum

The infrared spectrum of AFGL 618 (Kleinmann *et al.* 1978; Russell, Soifer, and Willner 1978) cannot be fitted by one color temperature and is best represented by a two component model: a hot dust component of temperature > 275 K and a cool dust component of the form $\nu^{1.5} B_\nu$ (95 K), where B_ν is the Planck function. In this respect it is extremely similar to the spectrum of NGC 7027 (cf. Kwok 1980). In analogy to Kwok's model for NGC 7027, we can associate the cool dust component with the remnant of the red-giant envelope and the hot dust component with dust newly formed in the H II region. Westbrook *et al.* (1975) measured a source size of 0″4 ± 0″2 at 11 μm. Since the infrared emission is moderately optically thick at $\lambda \sim 10$ μm (Westbrook *et al.* 1975; Russell, Soifer, and Willner 1978; Thronson 1981), the apparent size at 11 μm should be reasonably close to the actual size of the hot dust component. This is in rough agreement with the source size determined from our radio measurement, therefore supporting the above interpretation. It would be worthwhile to monitor the spectrum and apparent size in the infrared for possible evolution of this hot dust component.

d) The Evolutionary Status of AFGL 618

If AFGL 618 is indeed an extremely young planetary nebula, the mass of its central star can be obtained from the Paczyński core mass-luminosity relationship. Using $L = 3.2 \times 10^4$ $L_\odot$ ($D = 2$ kpc), we have $M_* \sim 1.06$ $M_\odot$. A star of such high mass evolves very rapidly in the preplanetary nebula stage, having a total evolution time from the asymptotic giant branch (AGB) to the maximum temperature point of the planetary nebula nucleus phase of only several decades (Paczyński 1971). This evolutionary time scale is comparable to the optical brightening time scale observed in AFGL 618. Such a rapid transition from AGB to planetary nebula also implies that most of the molecular/dust envelope ejected during the AGB should still be intact when the central star becomes hot enough to ionize the surrounding gas, exactly the situation we find in AFGL 618. The rarity of objects like AFGL 618 can therefore be explained by the high progenitor mass and short transit time across the H-R diagram.

When the central star of a protoplanetary nebula reaches temperatures $> 2 \times 10^4$ K, a fast stellar wind may be initiated. Existence of such stellar winds (with ejection velocities of 1000–3000 km s^{-1} and mass loss rates 10^{-9} to 10^{-7} $M_{\odot}$ yr^{-1}) is found in increasing number of planetary nebulae (Heap 1980; Castor, Lutz, and Seaton 1981). Collision of this wind with the remnant of the red-giant circumstellar envelope results in a shocked region which could produce the H_2 emission observed by Thronson (1981) in AFGL 618. This same collision would also lead to a snow-plow effect, creating a dense shell at the surface of interaction of the two winds. The shell will grow in mass as more of the wind material is being swept up and, when it is ionized by the central star, could have the appearance of a planetary nebula (Kwok, Purton, and FitzGerald 1978). The large mass contained in the molecular envelope of the planetary-nebula-to-be must be made up of wind material, supporting the interacting winds model of planetary nebula formation.

V. CONCLUSIONS

We have found strong evidence for an expanded H II region inside the molecular/dust envelope of AFGL 618. In 1980, the H II region had an angular size of $\sim 0''.2$, a mass of 10^{-4} to 10^{-3} $M_{\odot}$, and an emission measure exceeding 10^9 cm^{-6} pc. The expansion of the H II region is probably the result of the expansion of an ionization front caused by an increase in central star effective temperature and a larger output of UV photons. We suggest that the central star responsible for illumination of the reflection nebulae and the heating of the IR/molecular source has a mass of ~ 1 $M_{\odot}$ and is now rapidly evolving into the planetary nebula stage.

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