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RADIO EMISSION FROM AG PEGASI

P. C. GREGORY AND S. KWOK
Physics Department and Institute of Astronomy, University of British Columbia
AND
E. R. SEAQUIST
David Dunlap Observatory, University of Toronto
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ABSTRACT

Radio emission from the symbiotic nova AG Pegasi has been detected at 2.8 and 3.7 cm, and an upper limit has been obtained at 11 cm. The observations are interpreted as free-free emission from an ionized nebula formed by continuous mass ejection from the hot star. Our observations indicate a mass loss rate of $10^{-6}\ M_{\odot}\ \mathrm{yr}^{-1}$ and a total mass for the nebula of $7 \times 10^{-5}\ M_{\odot}$.

Subject headings: nebulae: individual — radio sources: general — stars: individual — stars: mass loss — stars: novae

I. INTRODUCTION

The variable star AG Pegasi belongs to a small group of stars referred to as symbiotic novae (Payne-Gaposchkin 1957). We have previously reported radio emission from one other symbiotic nova, R Aquarii (Gregory and Seaquist 1974). Unlike R Aqr, AG Peg is a well-established spectroscopic binary with a period of 820 days (Hutchings, Cowley, and Redman 1975). According to Boyarchuk (1967*a*), AG Peg consists of a normal M3 III and a hot low-luminosity WN6 star, similar to a planetary-nebula nucleus, embedded in a circumstellar nebula at a distance of 600 pc. Between 1850 and 1885 the brightness of AG Peg increased by ~3 mag. Since that time the visual magnitude has returned to nearly the value it was prior to 1850. According to Boyarchuk, the observed variations in m_v and in the emission line spectrum can be accounted for by a slowly developing flare from the hot component which gave rise to an expanding envelope. This envelope was opaque to optical continuum radiation until ~1900.

We report here the detection of radio emission from AG Peg at 2.8 and 3.7 cm, together with an upper limit on the flux density at 11 cm.

II. OBSERVATIONS

The measured radio flux densities for AG Peg are given in Table 1. The observations at 3.7 and 11 cm were obtained in 1973 October with the National Radio Astronomy Observatory three-element interferometer. The interferometer position obtained was $\alpha(1950) = 21^{h}48^{m}36^{s}.2 \pm 0^{s}.4$, $\delta(1950) = 12°23'27'' \pm 4''$, which agrees closely with the coordinates of AG Peg given in the Smithsonian Astrophysical Observatory Star Catalog of $\alpha(1950) = 21^{h}48^{m}36^{s}.185$, $\delta(1950) = 12°23'27''.35$.

The synthesized beam of the interferometer had dimensions of 3″ by 4″.6 to half power points, and the results obtained for AG Peg were consistent with an unresolved source. No additional sources were found in the 6′ field of view of the interferometer at 3.7 cm which indicated that single-dish measurements of the source should be free of confusion from other small angular diameter sources.

The observations at 2.8 cm were obtained in 1974 June with the Algonquin Radio Observatory 46 m telescope. These observations were made using a main and reference beam, each with half-power beamwidth (HPBW) of 2′.8, and with a separation of 8′.

III. INTERPRETATION

The radio observations are plotted in Figure 1 together with an upper limit at 10 μm by Glass and Webster (1973). Boyarchuk, Esipov, and Moroz (1966) in their paper give a graph of the relative spectral energy distribution from 0.3 μm to 2.5 μm for an

TABLE 1

MEASURED FLUX DENSITIES FOR AG PEGASI

Date	Frequency (MHz)	NRAO Interferometer Spacings (units of 100 m)	Flux Density (mJy)
1973 Oct.–Nov.	2695	27–19–18–8–1	< 6 (3 σ)
	8085	27–19–18–8–1	12 ± 2
1975 June	10522	(ARO 46 m telescope)	13 ± 2

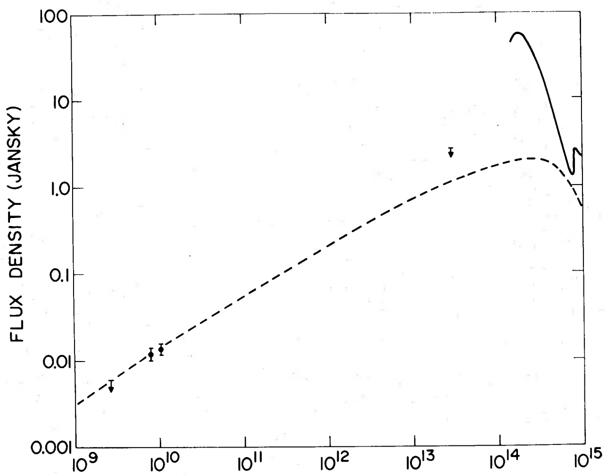

FIG. 1.—The spectrum of AG Peg from radio to ultraviolet wavelengths. The solid curve was derived from the results of Boyarchuk *et al.* (1966). The calculated free-free emission from the circumstellar nebula is shown by the dashed line.

epoch of 1964. We have converted these measurements to a flux density scale using their quoted value for $m_v = 7.9$ mag and interstellar-absorption $A_{VIS} = 0.25$ mag together with an assumed calibration for a 0.0 mag star at $\lambda = 5500$ Å of 0.0 mag $= 3.81 \times 10^{-23}$ W m^{-2} Hz^{-1}. The flux densities we derive from Figure 1 of the paper by Boyarchuk, Esipov, and Moroz (1966) are shown in Figure 1 of this paper by the solid curve.

Boyarchuk (1967*a*) has shown that the energy distribution in the optical continuum can be explained in terms of radiation from a cool M3 III, a hot WN6 star, and an ionized circumstellar nebula formed by mass outflow from the hot star. Free-free emission from the ionized nebula provides a likely explanation for the radio emission seen. We have therefore combined the radio and optical measurements to produce a model for the circumstellar nebula.

According to Boyarchuk (1967*b*) the optical emission lines provide evidence that at the present time, mass is flowing away from the hot star and that the nebula forms a filled sphere and not a comparatively thin shell. We therefore adopt a spherically symmetric gas density distribution of the form

$$N_e(r) = A/r^2 , \qquad (1)$$

consistent with a uniform mass loss rate. Here A is a constant, and r is the radial coordinate. Seaquist and Gregory (1973) and Wright and Barlow (1975) have shown that free-free emission from such a stellar wind geometry gives rise to a frequency spectrum for which S varies approximately as $\nu^{2/3}$. Our present radio measurements restrict the spectral index to lie in the range 0.5–1.8 which is consistent with this stellar wind model. The effective blackbody angular diameter of the emitting region is also frequency dependent (θ varies approximately as $\nu^{-2/3}$). If $T_e = 17{,}000$ K (Boyarchuk 1967*b*), then $\theta = 0\overset{''}{.}14$ at 3.7 cm, which corresponds to a radius 6×10^{14} cm. Provided the optically thick portion of the nebula is much larger than the radius of the hot star, the flux density at radio wavelengths ($h\nu \ll kT$), as given by Wright and Barlow (1975), is

$$S(\nu) = 23.2\left(\frac{\dot{M}}{\mu v_\infty}\right)^{4/3} \frac{\nu^{2/3}}{D^2} \gamma^{2/3} Z^{4/3} g^{2/3} \text{ Jy} . \qquad (2)$$

In equation (2) $\dot{M}$ = mass loss rate in $M_\odot$ yr^{-1}; μ = mean atomic weight of the gas; v_∞ = stellar wind velocity in km s^{-1}; γ = ratio of electron number density to ion number density; D = distance in kpc (=0.6); Z = effective nuclear charge; and g = the Gaunt factor which depends only weakly on the electron temperature and frequency.

If we assume that all the atoms in the nebula are singly ionized, then $\mu = 1.26$ (Allen 1973), $\gamma = 1$, and $Z = 1$. Equation (2) with $T_e = 17{,}000$ K and $S = 12$ mJy at $\nu = 8085$ MHz yields

$$\frac{\dot{M}}{v_\infty} = 7 \times 10^{-9}\, M_\odot \text{ yr}^{-1} \text{ km}^{-1} \text{ s} .$$

Boyarchuk has estimated the expansion velocity $v_\infty = 114$ km s^{-1} which then leads to a mass loss rate $= 1.0 \times 10^{-6}\, M_\odot$ yr^{-1}. The constant A in equation (1) can be evaluated from the mass loss rate using the relation

$$A = \frac{\dot{M}}{4\pi\mu m_{\rm H} v_\infty} ,$$

which yields $A = 2.12 \times 10^{35}$ cm^{-1}.

Boyarchuk (1967*a*) has estimated the fraction of the optical continuum originating in the nebula. Assuming free-bound and free-free emission, he derived

$$\int N_e^2 dV = 8.4 \times 10^{60} \text{ cm}^{-3} ,$$

where V is the volume of the nebula. We may combine this result with our model for the gas density distribution to derive the inner radius of the nebula since

$$\int N_e^2 dV = 4\pi A^2 \left(\frac{1}{R_i} - \frac{1}{R_o}\right) \approx \frac{4\pi A^2}{R_i} .$$

This yields $R_i = 6.7 \times 10^{10}$ cm, which agrees very closely with Boyarchuk's estimate of the radius of the WN6 star of 6.3×10^{10} cm. This agreement strongly supports our model for the gas density distribution in the nebula and furthermore supports Boyarchuk's view that continuing mass ejection is occurring at the present time from the hot star.

We have computed the free-free emission spectrum expected from our model of the nebula at radio, infrared, and optical wavelengths using an inner radius $R_i = 6.7 \times 10^{10}$ cm and outer radius R_0 chosen so that the spectrum passed just below our upper limit at 11 cm. This is shown by the dashed curve in Figure 1. The effect of an outer boundary to the nebula is to steepen the spectrum at the longest radio wavelengths without altering the spectrum at short wavelengths. We found that the maximum outer radius consistent with our 11 cm upper limit was $R_0 = 2.5 \times 10^{16}$ cm. Another estimate of R_0 can be obtained by assuming that if mass ejection began in ~ 1885, the time of maximum light, then the size of the nebula in 1973 would have been 3×10^{16} cm. For comparison the separation between the two stars is $\sim 5 \times 10^{13}$ cm (Boyarchuk 1967*b*) so the circumstellar nebula surrounds both stars. The total mass of the nebula is given by

$$M = 4\pi\mu A m_h(R_o - R_i) \simeq 4\pi\mu A m_h R_o \,.$$

Assuming $R_o = 2.5 \times 10^{16}$ cm, then $M = 7 \times 10^{-5}$ $M_\odot$.

IV. DISCUSSION

Merrill (1958) suggested that some symbiotic stars including AG Peg may represent the immediate precursor stage to a planetary nebula. At the time it was supposed that these symbiotic stars were cool giants in the process of losing their envelopes. Since that time a number of symbiotic stars including AG Peg, BF Cyg, and RW Hya were found to be binary systems. More recently Boyarchuk (1974) has proposed that all symbiotic stars are binaries consisting of a cool giant and a small hot star embedded in an ionized nebula. If the cool star is a normal giant of luminosity class III, the hot star is located in the same region of the H-R diagram as the central stars of planetary nebulae and the hot components of novae. Because of this and other similarities between symbiotic stars and planetary nebulae, Boyarchuk (1974) argues that if the nuclei of planetary nebulae are an evolutionary stage of a single star, then perhaps symbiotic stars are the same evolutionary stage for binaries in which the initially more massive star has evolved into the nucleus of a planetary nebula. If this evolutionary picture for symbiotic stars is correct, then it is likely that the nebulae of symbiotic stars are formed by gas ejected from the hot star, rather than mass loss from the existing cool star which is excited by the hot star, as has been proposed by Mammano and Ciatti (1975).

In this paper we have attempted to interpret our radio observations in terms of free-free emission from a nebula in which the gas density and electron density have an inverse square law dependence on radius, corresponding to a uniform mass loss rate. For this model we are able to derive an inner radius of the nebula which corresponds closely to the radius of the hot star, thus lending support to the hypothesis that the gas was ejected from the hot star rather than the cool star. Our model for the gas density distribution in the nebula leads to a definite prediction for the spectrum of the free-free emission expected at radio and infrared wavelengths which is shown by the dashed curve in Figure 1. If the mass-loss rate from the hot star has not been uniform since the initial brightening in 1885, then the gas density distribution in the nebula would be different from what we have assumed and give rise to a different radio and infrared spectrum. At the present time the spectrum of the free-free emission is not sufficiently well known to determine the gas density distribution. Further radio and infrared observations are required for this purpose.

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P. C. GREGORY and S. KWOK: University of British Columbia, Dept. of Physics, Vancouver, B.C. V6T 1W5, Canada

E. R. SEAQUIST: David Dunlap Observatory, University of Toronto, Richmond Hill, Ontario L4C 4Y6, Canada