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EXPANSION OF THE PLANETARY NEBULA SURROUNDING FG SAGITTAE*

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ABSTRACT

Large-scale spectrograms have been obtained of the symmetrical emission nebulosity surrounding the peculiar variable FG Sge; the dispersion was 11 Å mm^{-1}, at the coudé spectrograph of the 120-inch (3-meter) telescope. The Hα and [N II] lines have the form of elliptical rings, from which are inferred a nebular expansion velocity of 34 ± 1 km s^{-1}, and a mean velocity of $+38 \pm 1$ km s^{-1}. The latter is very near the stellar velocity of about $+37$ km s^{-1}. The angular radius of the nebula (18″) and a distance of 2.5 kpc then lead to a quasi-expansion age of 6000 years for the nebula. These results give strong support to the proposal that the envelope surrounding FG Sge is a completely typical planetary nebula.

Subject headings: planetary nebulae — stars, individual

I. INTRODUCTION

The peculiar variable FG Sge is centrally located in a faint, nearly circular nebulous envelope having a mean radius of about 18″. Photometrically, the star has brightened steadily from fainter than $m_{pg} = 13.6$ in 1894 (the total light at the early observations was dominated by the contribution of an unresolved companion) to a peak of $B = 9.5$ in 1968, following which the B magnitude has since declined slightly (Wenzel and Fürtig 1971). The nebulosity has a pure emission-line spectrum like that of a planetary nebula of moderate excitation, and for this reason and on account of its regular outline it has been regarded as a planetary nebula by most investigators. The most recent examination of the matter has been by Faulkner and Bessell (1970), who pointed out that (*a*) the observations plus the assumption of a typical planetary nucleus mass for FG Sge make possible the construction of a self-consistent set of parameters for the star as it brightened, and (*b*) the nebula falls in an area of the [$\log S(H\beta)$, $\log n_e$]-diagram appropriate to expanding ionized shells. On these grounds, they also concluded that the envelope is an old planetary nebula.

It would be important to be able to conclude that the event now under way at FG Sge is an actual example of the ejection of a new planetary-nebula shell before our eyes (as proposed by Herbig and Boyarchuk 1968), and that the 18″ nebulous envelope represents an older product of the same process. Substantial support for the second conclusion would be provided if it could be shown that the nebula is in expansion about FG Sge at a rate typical for planetary envelopes, and has a reasonable expansion age. We have now made spectroscopic observations which demonstrate precisely that.

II. OBSERVATIONS

Two new spectrograms of the FG Sge nebulosity were obtained on 1972 September 20 with the coudé spectrograph of the 120-inch (3-meter) reflector. The grating was a double-diamond-ruled 900 grooves per mm Bausch and Lomb product of 8 by 12 inches ruled area. When illuminated by a 9.5-inch aperture collimator, and operated

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in the second-order red, this grating plus the 20-inch Schmidt camera used in Newtonian mode and a cooled Varo image intensifier produces a dispersion of 11 Å mm^{-1} near Hα. Exposure times of 1 hour, with a 0″.95 × 38″ slit crossing the nebula nearly diametrically, gave well-exposed images of Hα and the nearby [N II] λ6583.39 line; the [N II] line λ6548 has one-third the intensity of λ6583 and was somewhat too weak for easy measurement. Hα is somewhat more diffuse than the stronger [N II] line, as is often the case in nebulae. The usual image rotator was not used for these observations, so the field rotated about 15° on the slit during the exposure. The diagrams of slit location in the nebula (fig. 1) show its positions at mid-exposure.

On these spectrograms both Hα and the [N II] lines are fully resolved into elliptical rings containing a certain amount of structure (fig. 1). There are some problems in precise measurement of the ring dimensions, on account of field distortion in the intensifier and the infrequency of Ne I comparison lines in this spectral region. The plates were measured visually in a 2-coordinate engine, and were reduced by a double interpolation scheme as follows. If x and y are the coordinates parallel and perpendicular to the dispersion, respectively, each comparison line was measured (both direct and reverse) in x,y at six points along its length. Fourth-order polynomials $x = f(y)$ fitted to these points defined contours of constant λ for those wavelengths. Each Hα or [N II] ring was measured at eight points around its periphery (see fig. 2), and the corresponding comparison-line x value for each of these y's was obtained from the constant-λ polynomials. The value of λ was then obtained from a third-order polynomial in x fitted to the proper points of the comparison-line contours, from which followed the corresponding radial velocities for that point in the nebular line.[1] The results are in table 1.

The measurements were difficult at some points where the nebular line width was substantially above the instrumental resolution (the projected slit width was about 13 km s^{-1}). The lines were especially diffuse at the ends of their major axes (points 3,7), and best defined at the minor axis extremities (points 1,5). Probably the total uncertainty of a single tabular value is 4–5 km s^{-1}, but the uncertainty of the difference of a pair of values having the same y is less; the velocity difference between points 1 and 5 is probably uncertain to about 1–2 km s^{-1}. Table 2 contains the values of the local expansion velocity, $|\frac{1}{2}(v_i - v_j)|$, and the local mean velocity $\frac{1}{2}(v_i + v_j)$ for all the appropriate pairs of i,j.

TABLE 1

RADIAL VELOCITIES (in km s^{-1}) AT SELECTED POINTS IN THE EMISSION-LINE STRUCTURE

	[N II] 6583.39 Å		Hα 6562.817 Å	
POSITION IN LINE	Slit Position AB	Slit Position CD	Slit Position AB	Slit Position CD
1............	+70.5	+72.3	+68.5	+72.6
2............	65.7	67.0	61.0	64.9
3............	37.1	39.9	38.6	35.3
4............	11.4	8.7	14.0	4.9
5............	4.8	4.8	6.0	4.7
6............	12.5	15.4	12.6	13.0
7............	34.4	43.0	38.3	37.9
8............	+66.0	+68.0	+59.4	+65.6

NOTE.—The "position in line" numbers of the first column refer to the points indicated in fig. 2. The "slit positions" AB and CD refer to the slit locations shown in fig. 1.

[1] Since only four comparison lines were available, no estimate of the uncertainty of the fit of this polynomial was possible.

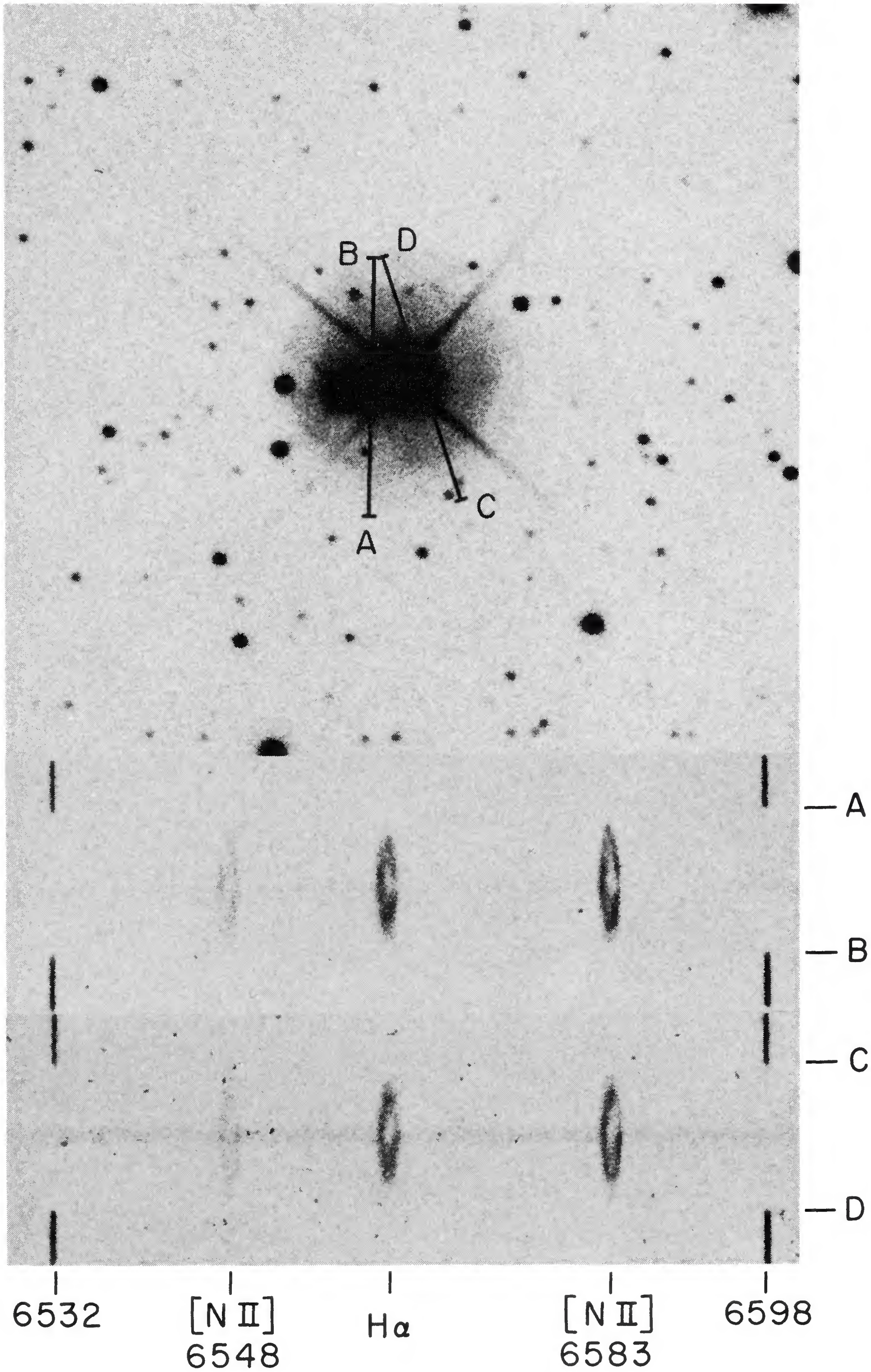

FIG. 1.—(*above*) Direct photograph of the nebula at FG Sge in red light, with the locations of the spectrograph slit at mid-exposure indicated for the two spectrograms shown below. The slit length in both cases was 38″ and the width 0″.95, the latter corresponding to the very short bars at the ends of the lines. The original plate was taken in the 6000–6700 Å region with the 120-inch (3-meter) reflector on 1963 July 1. North is at the top and east to the left. (*below*) Hα and the [N II] λλ6548, 6583 emission lines in the nebula. The spectrogram whose slit length is indicated by AB is EC-10928, position angle at midexposure = 356°; CD is EC-10929, p.a. = 14°. Both exposures were 1 hour, dispersion 11 Å mm^{-1}. Note that the scale of the spectrograms perpendicular to the dispersion is somewhat less than that of the direct photograph. The comparison lines are of neon.

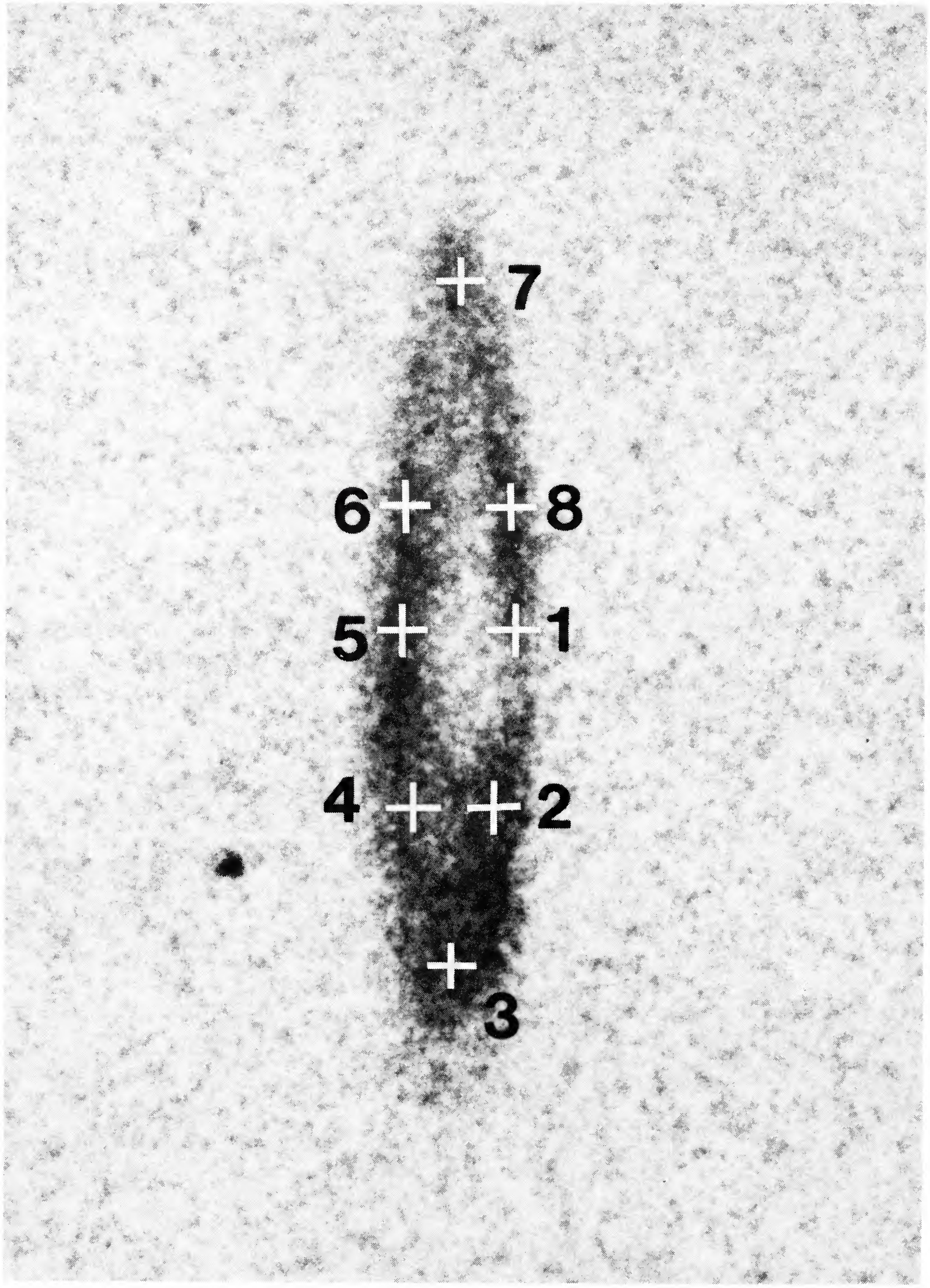

FIG. 2.—Points in the elliptical emission lines whose velocities are given in table 1. The line shown is λ6583 from the spectrogram identified as AB in fig. 1.

TABLE 2

EXPANSION VELOCITY AND MEAN VELOCITY (km s^{-1}) IN THE FG SAGITTAE NEBULA

Positions in Line (i, j)	[N II] 6583.39 Å $v_{exp} = \|\frac{1}{2}(v_i - v_j)\|$ AB*	CD*	[N II] 6583.39 Å $v_{neb} = \frac{1}{2}(v_i + v_j)$ AB*	CD*	Hα 6562.817 Å v_{exp} AB*	CD*	Hα 6562.817 Å v_{neb} AB*	CD*
3	...	...	+37.1	+39.9	...	...	+38.6	+35.3
2, 4	27.1	29.1	38.6	37.8	23.5	30.0	37.5	34.9
1, 5	32.9	33.8	37.6	38.6	31.2	34.0	37.3	38.7
6, 8	26.7	26.3	39.3	41.7	23.4	26.3	36.0	39.3
7	...	...	+34.4	+43.0	...	...	+38.3	+37.9

NOTE.—Coding is the same as for table 1.

* Slit position.

The mean v_{exp} from both plates, reduced to the center of the projected nebular disk on the assumption of isotropic expansion to a radius of 18″, is 34 ± 1 km s^{-1}. The mean velocity from all pairs of lines on both plates is $\langle v_{neb} \rangle = +38 \pm 1$ km s^{-1}; the result would be the same if only the results from the well-defined points 1,5 were used.

The data may also be examined for any evidence of inclination of the major axes of the rings, as is often observed in planetary nebulae and has sometimes been ascribed to rotation. There is no clear evidence of a velocity difference in excess of 2–3 km s^{-1} between the two limbs of the nebula in the slit orientations used here, but of course the observation should be repeated with the slit in other position angles.

III. DISCUSSION AND CONCLUSIONS

The well-determined expansion velocity of 34 km s^{-1} is completely typical for planetary nebulae, whose v_{exp}'s range from very small values up to about 100 km s^{-1} (Wilson 1950). The distance of 2.5 kpc for FG Sge estimated by Herbig and Boyarchuk (1968) from the increase in reddening with distance in this direction is slightly to be preferred to the more complicated estimate (1.5 kpc) of Faulkner and Bessell (1970), which involves an assumed mass for the central star together with the observed dependence of g and T_{eff} upon spectral type and luminosity class for normal stars. The observed 18″ radius of the nebula is then 0.22 pc, which yields a quasi-expansion age of 6100 years. This also is a quite representative value for planetary nebulae (Whipple 1938).

The mean nebular velocity of $\langle v_{neb} \rangle = +38$ km s^{-1} may be compared to the mean stellar velocity. This latter is probably best determined by Herbig and Boyarchuk's measurements of the stellar absorption lines of Fe II, Ti II, Si II, etc.; the Balmer lines were distorted by shell effects, particularly during the early part of the interval 1960–1967 that is covered by the published coudé observations. The weighted $\langle v_* \rangle$ was +39 km s^{-1} in 1965 plate, and +34 km s^{-1} in 1967. There is some suspicion that the mean velocity, even from these relatively well-behaved lines of the ionized metals, is slightly variable, but a $\langle v_* \rangle$ near +37 km s^{-1} seems compatible with all the better data of that era. This is surprisingly close to the value of $\langle v_{neb} \rangle = +38$ km s^{-1} obtained from the nebular emission lines.

Shell components indicate that material is rising in the immediate neighborhood of the star at a velocity substantially higher than the expansion velocity given by the nebular spectrum: Herbig and Boyarchuk estimated an expansion velocity of about 70 km s^{-1} for the material very near the star, from the structure of Hα in 1960 when the shell phenomena were more conspicuous than at any time since. It would appear either that the new shell is being ejected at a higher velocity than the old, or that the shells are decelerated as they recede from the star.

The interpretation of these numbers awaits a detailed model of FG Sge. At the moment, we only note that the radial velocities of FG Sge and its nebula are in close agreement, and thus that there can no longer be any doubt (if any existed) of their organic association.

We conclude that there are no spectroscopic or kinematic data which conflict with the proposal that the nebula at FG Sge is a completely typical planetary nebula expanding at about 34 km s^{-1}, with a quasi-expansion age of about 6000 years, and in the mean sharing the radial velocity of the central star.

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