The Astrophysical Journal, 163:L99–L104, 1971 February 1

THE GUM NEBULA: FOSSIL STRÖMGREN SPHERE OF THE VELA X SUPERNOVA

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Received 1970 November 12; revised 1970 December 11

ABSTRACT

A physical model for the Gum Nebula is derived from dispersion measures of pulsars, the nebular Hα emission measure, rocket observations of the Lα absorption in the spectra of γ^2 Vel and ζ Pup, and photometry of stars near γ^2 Vel. The objects γ^2 Vel and ζ Pup are not capable of ionizing the nebula. We suggest that the nebula was produced by radiation from the supernova outburst that gave rise to the Vela X remnant and pulsar PSR 0833−45.

I. DISTANCE TO γ VELORUM

The distance to γ^1 and γ^2 Vel has been the subject of several investigations. The results include 200 pc (Whiteoak 1961) and 220 pc (Gum 1952), and range upward through 350 pc (Hanbury Brown *et al.* 1970) or slightly less (Baschek 1970) to 460 pc (Smith 1968). There appears to be a small group of stars (possibly a B association) around γ^2 Vel, and photoelectric Hβ indices and Strömgren four-color measurements have been obtained for seventeen of these stars by one of us (D. L. C.) at the Cerro Tololo Inter-American Observatory. The measurements yield distance moduli for thirteen of the stars; of these thirteen, three stars are definitely much farther away than the others and one is either much closer or is a double star. The remaining nine stars (data given in Table 1) yield an average distance modulus of 8.3 or a distance of 460 pc, in agreement with Smith's (1968) result for γ^2 Vel. It seems likely, if not certain, that γ^2 Vel is a member of this group.

The Vela X supernova remnant lies at a distance of about 500 pc according to Milne (1968*a*, *b*). Harris (1962) derived a distance of 460 pc to the remnant by use of Shklovsky's radio method. He obtained a slightly larger value from the filaments. The pulsar PSR 0833−45 (Large, Vaughan, and Mills 1968) is clearly associated with the Vela X remnant (the evidence is reviewed by Kristian 1970), and is therefore at the same distance. If γ^2 Vel and PSR 0833−45 are both about 460 pc from the Sun, then their angular separation (4°) corresponds to a linear separation of only 35 pc.

* Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

1971ApJ...163L..99B

TABLE 1

PHOTOMETRY OF THE γ VELORUM REGION*

HR	β	n_1	$(b-y)$	c_1	n_2	MK	$(b-y)_0$	$E(b-y)$	A_V	V	M_V	dm
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
3055........	2.592	3	−0.05	−0.08	5	B0 III	−0.13	0.08	0.34	4.10	−4.1	7.9
3089........	2.611	3	−0.10	+0.01	5	B1.5 Vp	−0.12	0.02	0.08	4.62	−3.6	8.1
3204........	2.616	3	−0.08	+0.23	1	B2 IV–V	−0.09	0.00	0.00	5.20	−3.3	8.5
3206........	2.592	3	−0.10	0.00	5	B1 IV	−0.12	0.02	0.08	4.25	−4.1	8.2
3207........	2.485	3	−0.43	−0.46	3	WC8+O7	...	...	...	1.82	...	...
3227........	2.678	3	−0.06	+0.35	1	B3 V	−0.08	0.02	0.08	5.94	−1.7	7.6
3250........	2.637	3	−0.09	+0.14	1	B2 IV–V	−0.10	0.01	0.04	6.02	−2.8	8.8
3294........	2.613	3	−0.06	+0.07	4	B1.5 III	−0.12	0.06	0.25	4.82	−3.5	8.1
3358........	2.632	3	−0.05	+0.13	1	B2 IV	−0.11	0.06	0.25	5.32	−2.9	8.0
3375........	2.653	3	−0.09	+0.30	1	B1.5 V	−0.08	0.00	0.00	6.50	−2.3	8.8

NOTE.—Units are magnitudes in cols. (2),(4),(5), and (8)–(13).

* Col. (3), number of observations of β; col. (6), number of observations in four-color system; col. (7), MK type from Hiltner, Garrison, and Schild (1969); col. (8), from calibration by Crawford (1970); col. (10), $A_V = 4.2E(b-y)$; col. (11), apparent visual magnitude from Yale *Bright Star Catalogue;* col. (12), absolute visual magnitude from Hardie and Crawford's (1961, p. 857) relation for "all stars"; col. (13), distance modulus $= V - M_V - A_V$.

II. NEBULAR MODEL FROM MEASUREMENTS OF INTERSTELLAR PARAMETERS

The interstellar measurements that can be made in the direction of the Gum Nebula include (1) the nebular emission measure E.M., (2) the dispersion measures D.M. of pulsars, (3) the neutral-hydrogen measure H.M., and (4) the optical extinction A_V. From these data, a reasonably detailed picture of the interstellar medium between the Sun and the Vela region may be derived. In particular, if we assume that the radius of the nebula is comparable to the distance to γ^2 Vel, we can write

$$\text{E.M.} \approx \langle N_e^2 \rangle 2L\,, \quad \text{D.M.} \approx \langle N_e \rangle L\,, \quad \text{H.M.} \approx \langle N_\text{H} \rangle L\,, \tag{1}$$

and

$$\frac{1}{\text{X}} = \frac{\langle N_e \rangle^2}{\langle N_e^2 \rangle}\,, \tag{2}$$

where N_e is the electron density (cm^{-3}), N_H is the neutral-hydrogen density (cm^{-3}), L is the nebular radius (pc), and 1/X is the fraction of the nebular volume that is occupied by matter on the usual approximation that the gas is concentrated into clumps. The factor of 2 in the equation for E.M. results from the fact that the E.M. measurement refers to the whole path through the nebula, whereas the D.M. and H.M. data pertain to a length of 1 nebular radius.

The emission measure from Hα observations (Gum 1952) varies from 600 cm^{-6} pc in the faintest observable parts of the Gum Nebula to 3000 cm^{-6} pc in the brightest parts near γ^2 Vel. We adopt the geometrical mean of 1300 cm^{-6} pc as a representative value.

The dispersion measure of PSR 0833−45 is 69.2 cm^{-3} pc (Ables, Komesaroff, and Hamilton 1970). Three other pulsars, MP 0736, MP 0835, and MP 0940, are observed through the Gum Nebula with dispersion measures of 100, 120, and 145 cm^{-3} pc, respectively (cf. Prentice and ter Haar 1969). From these data, it seems likely that PSR 0833−45 lies near the center of the Gum Nebula and that the other three pulsars lie beyond the nebula. Using the observations of all four pulsars, we estimate both the arithmetic and geometric means of the dispersion measures corresponding to 1 nebular radius as 63 cm^{-3} pc, if the nebula is the dominant contributor to the measured dispersions.

The neutral-hydrogen measure, as determined from rocket observations of Lα absorption in γ^2 Vel and ζ Pup, is about 25 cm^{-3} pc (Stecher 1968, 1970; Smith 1970; Morton, Jenkins, and Brooks 1969). This neutral hydrogen might be distributed throughout the region between the Sun and these two stars. However, we note that a path length of 60 pc through the neutral hydrogen in the solar vicinity (density $\approx$ 0.4 cm^{-3}, discussed below) could account for the observed H.M. The observation of similar H.M. for γ^2 Vel and ζ Pup also lends support to the idea that the neutral hydrogen lies close to the Sun. Manchester, Murray, and Radhakrishnan (1969) and Gordon and Gordon (1970) attempted to detect the 21-cm line in absorption against PSR 0833−45 and found upper limits to the optical depth of 0.05 and 0.08, respectively.

The neutral-hydrogen density near the Sun can be inferred from 21-cm line studies in two ways: (1) The column density of hydrogen atoms perpendicular to the galactic plane is measured; then knowing the thickness, one obtains the average density. (2) The velocity profiles can be fitted to a rotational model of the Galaxy to obtain a local value for the zero-velocity profile (Kerr and Westerhout 1965). McGee and Murray (1961) derived 0.46 hydrogen atoms cm^{-3} by the first method; this value is close to the average density quoted by Kerr and Westerhout. Goldstein and MacDonald (1969) obtained a somewhat lower value depending on the assumed scale height. We have adopted an average value of 0.4 cm^{-3}.

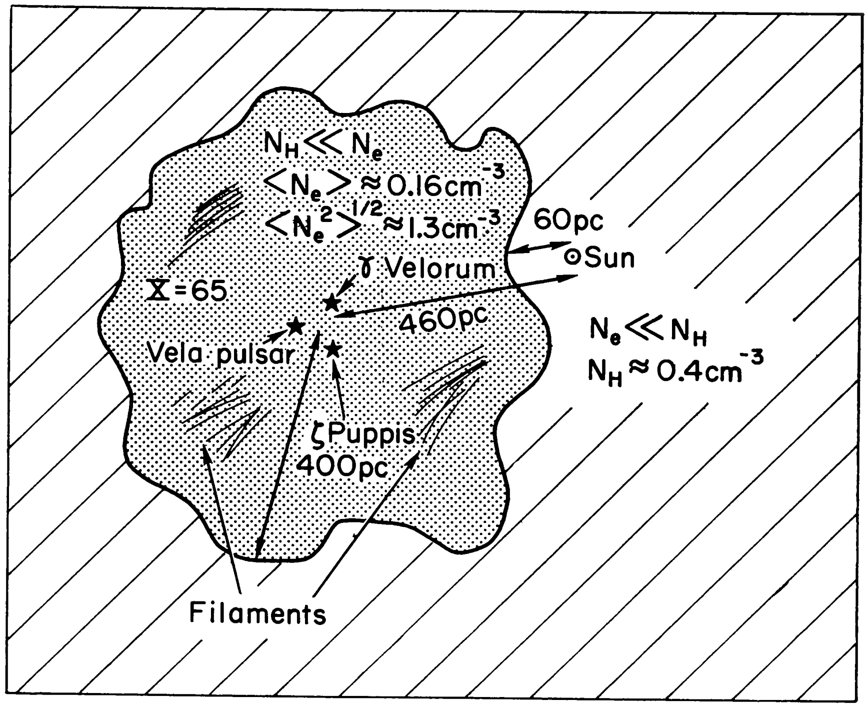

FIG. 1.—Schematic representation of the model for the region of the Gum Nebula, as derived in § II

Taking E.M. $\approx$ 1300 cm^{-3} pc, D.M. $\approx$ 63 cm^{-3} pc, H.M. $\approx$ 25 cm^{-3} pc, and $L \approx$ 400 pc, we find from equations (1) and (2) that

$$\langle N_e \rangle \approx 0.16 \text{ cm}^{-3}\,, \quad \langle N_e^2 \rangle \approx 1.63 \text{ cm}^{-6}\,, \quad \langle N_e \rangle_{\text{rms}} \approx 1.28 \text{ cm}^{-3}\,, \quad \langle N_{\text{H}} \rangle \approx 0.062 \text{ cm}^{-3}\,;$$

$$\text{X} \approx 65\,, \quad \text{X}\langle N_{\text{H}} \rangle \approx 4 \text{ cm}^{-3}\,, \quad \text{X}\langle N_e \rangle \approx 10 \text{ cm}^{-3}\,.$$

The nebular matter seems to be highly concentrated in filaments, in a manner reminiscent of the neutral interstellar gas (cf. Spitzer 1968*a*). This conclusion is consistent with Gum's (1952) classification of the nebula as a "scattered Class III nebulosity." (See also the descriptions by Gum 1955, Plate I, and by Abt, Morgan, and Strömgren 1957.) The present model, in which the neutral hydrogen is taken as being near the Sun, is depicted schematically in Figure 1.

It can be seen from Table 1 that the optical absorption in the direction of the γ Vel region is considerably smaller than the usual value of 1 mag kpc^{-1}. In particular, $A_V =$ 0.08 mag for γ^1 Vel (HR 3206). However, the relative abundance of gas to dust as indicated by the expression $N_e L/A_V$ (where L is now expressed in kpc) is of order unity, which is typical of the general interstellar medium.

III. THE ORIGIN OF THE GUM NEBULA

Gum (1952) considered that the nebula is a Strömgren sphere that is ionized by γ^2 Vel (WC8 + O7) and ζ Pup (O5f). The temperatures of these stars have recently been determined (Stecher 1968, 1969, 1970; Hanbury Brown *et al.* 1970; Davis *et al.* 1970). Since their effective temperatures are found to be only 30000°–40000° K, it is clear that they could not have produced the observed ionization. For example, the classical Strömgren sphere of an O5 star ($T_{\text{eff}} \approx$ 56000° K, $R/R_\odot \approx 7$) in a medium with rms electron density of 1 cm^{-3} has a radius of only 100 pc (Strömgren 1939, 1948; Spitzer 1968*b*, p. 117). For three such stars (probably an overestimate of the ionizing capacity of the stars in this part of the sky), the Strömgren sphere would have a radius of 144 pc.

We estimate the energy required to produce the observed ionization of the Gum Nebula by representing the nebula as a cylinder of radius 400 pc and height 100 pc. Then the volume V is 1.35×10^{63} cm^3, and

$$V\langle N_e \rangle \approx 2.1 \times 10^{62} \text{ electrons} .$$

The number of ionizing photons, if we neglect recombination, must at least equal the number of electrons. If we assume an average energy of 15 eV per photon, then 5×10^{51} ergs were required to ionize the Gum Nebula. It would appear that the only likely source of this much energy below the Lyman limit is a supernova (Colgate and White 1966). We are therefore led to suggest that the Gum Nebula was produced by the supernova outburst that gave rise to the pulsar PSR 0833−45 and the Vela X remnant. The large value of X found above is in accord with an origin of the nebular ionization in a brief event such as a supernova outburst: at a sound speed of 10 km s^{-1}, thermal motions have only dispersed matter in a filament by $\backsim$0.1 pc since the ionization occurred. As the present model ascribes the ionization of the Gum Nebula to a source that no longer exists to maintain it, we suggest the term "fossil Strömgren sphere" to describe it. We note that Morrison and Sartori (1969) suggested that "giant" H II regions are produced by the ionizing radiation from Type I supernovae.

The age of PSR 0833−45 is estimated at 1.1×10^4 years by Reichley, Downs, and Morris (1970). Assuming that this is also the age of the Gum Nebula, we may ask how much the nebular ionization has decayed up to the present time. The recombination rate (Spitzer 1968*b*) at a temperature of 10^4 °K is 2.6×10^{-13} N_e^2 cm^{-3} s^{-1}, which varies as $T^{-1/2}$ and which corresponds to a recombination time of $(1.1 \times 10^5)/N_e^2$ years. Since the cooling time (Spitzer 1968*b*) is $(2 \times 10^4)/N_p$ years, where N_p is the proton density (cm^{-3}), and since the initial temperature of the nebula must have been very high, we conclude that recombination has occurred significantly only in the densest filaments, i.e., where $N_e \gtrsim 10$ cm^{-3}. The approximate nature of the model, in which all of the matter is confined to the filaments, must overestimate the rate of recombination. In addition, the ultraviolet radiation of γ^2 Vel and ζ Pup surely helps to maintain the present high degree of ionization in the nebula.

On the present model, the ionization of the Gum Nebula does not extend to the Sun. Thus, an interaction between the solar wind and the neutral interstellar medium is possible (Patterson, Johnson, and Hanson 1963; Brandt 1964, 1971; Blum and Fahr 1970).

It is interesting to speculate on the relation between γ^2 Vel, ζ Pup, and PSR 0833−45. It has been suggested (cf. Smith 1955) that γ^2 Vel and ζ Pup have a common origin. The pulsar is clearly in a more highly evolved state than either of these two stars. Perhaps all three objects were formed at the same time and the most massive one has now reached the most advanced evolutionary state with which we are familiar. We have also noted above that γ^2 Vel may be associated with an association. Further studies of these objects and the surrounding nebula should yield information on many aspects of the interaction of a supernova with the interstellar medium, and perhaps on stellar evolution as well.

REFERENCES

Ables, J. G., Komesaroff, M. M., and Hamilton, P. A. 1970, *Ap. Letters*, **6**, 147.
Abt, H. A., Morgan, W. W., and Strömgren, B. 1957, *Ap. J.*, **126**, 322.
Baschek, B. 1970, *Astr. and Ap.*, **7**, 318.
Blum, P. W., and Fahr, H. J. 1970, *Astr. and Ap.*, **4**, 280.

Brandt, J. C. 1964, *Icarus*, **3**, 253.
———. 1971 (to be published).
Colgate, S. A., and White, R. H. 1966, *Ap. J.*, **143**, 626.
Crawford, D. L. 1970, in *Stellar Rotation*, ed. A. Slettebak (Dordrecht: D. Reidel Publishing Co.), p. 204.
Davis, J., Morton, D. C., Allen, L. R., and Hanbury Brown, R. 1970, *M.N.R.A.S.*, **150**, 45.
Goldstein, S. J., Jr., and MacDonald, D. D. 1969, *Ap. J.*, **157**, 1101.
Gordon, K. J., and Gordon, C. P. 1970, *Ap. Letters.*, **5**, 153.
Gum, C. S. 1952, *Observatory*, **72**, 151.
———. 1955, *Mem. R.A.S.*, **67**, 155.
Hanbury Brown, R., Davis, J., Herbison-Evans, D., and Allen, L. R. 1970, *M.N.R.A.S.*, **148**, 103.
Hardie, R., and Crawford, D. L. 1961, *Ap. J.*, **133**, 843.
Harris, D. E. 1962, *Ap. J.*, **135**, 661.
Hiltner, W. A., Garrison, R. F., and Schild, R. E. 1969, *Ap. J.*, **157**, 313.
Kerr, F. S., and Westerhout, G. 1965, in *Galactic Structure*, ed. A. Blaauw and M. Schmidt (Chicago: University of Chicago Press), p. 167.
Kristian, J. 1970, *Ap. J.* (*Letters*), **162**, L103.
Large, M. I., Vaughan, A. E., and Mills, B. Y. 1968, *Nature*, **220**, 340.
McGee, R. X., and Murray, J. D. 1961, *Australian J. Phys.*, **14**, 260.
Manchester, R. N., Murray, J. D., and Radhakrishnan, V. 1969, *Ap. Letters*, **4**, 229.
Milne, D. K. 1968*a*, *Australian J. Phys.*, **21**, 201.
———. 1968*b*, *ibid.*, p. 501.
Morrison, P., and Sartori, L. 1969, *Ap. J.*, **158**, 541.
Morton, D. C., Jenkins, E. B., and Brooks, N. H. 1969, *Ap. J.*, **155**, 875.
Patterson, T. N. L., Johnson, F. S., and Hanson, W. B. 1963, *Planet. and Space Sci.*, **11**, 767.
Prentice, A. J. R., and Haar, D. ter. 1969, *Nature*, **222**, 964.
Reichley, P. E., Downs, G. S., and Morris, G. A. 1970, *Ap. J.* (*Letters*), **159**, L35.
Smith, A. M. 1970, *Ap. J.*, **160**, 595.
Smith, H. J. 1955, dissertation, Harvard University.
Smith, L. F. 1968, *M.N.R.A.S.*, **140**, 409.
Spitzer, L., Jr. 1968*a*, in *Nebulae and Interstellar Matter*, ed. B. M. Middlehurst and L. H. Aller (Chicago: University of Chicago Press), p. 1.
———. 1968*b*, in *Diffuse Matter in Space* (New York: Interscience Publications).
Stecher, T. P. 1968, in *Wolf-Rayet Stars*, ed. K. B. Gebbie and R. N. Thomas (N.B.S. Special Publication, No. 307), p. 65.
———. 1969, *A.J.*, **74**, 99.
———. 1970, *Ap. J.*, **159**, 543.
Strömgren, B. 1939, *Ap. J.*, **89**, 526.
———. 1948, *ibid.*, **108**, 242.
Whiteoak, J. B. 1961, dissertation, Australian National University.