X-RAYS FROM THE VELA-PUPPIS COMPLEX

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Abstract

A review of X-ray observations in the vicinity of the Gum Nebula is presented. There is little doubt that the filamentary nebula Stromlo 16, the radio source Vela X and the extended X-ray object Vel XR-2 are indications of the same, relatively nearby, supernova remnant. X-ray absorption measurements are consistent with a distance of 500 ± 100 pc. The observed X-ray spectra have not yet distinguished between thermal bremsstrahlung and synchrotron radiation as the source mechanism. A search for low energy X-ray emission lines, both within the 5° diameter remnant and in the larger Gum Nebula, may provide an important test for models of supernova remnant evolution.

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Present views on the age and distance of the Vela supernova remnant place it as the nearest ($\sim$ 460 parsecs) such object with age less than 50,000 years yet discovered. As such, its effect on the nearby interstellar medium may be considerable. With an associated radio source, magnetic field pattern, filaments bright in optical emission lines, an active pulsar, and possibly a large, high temperature fossil H II region, it is clear that this area provides a fine laboratory for investigating supernova remnants at close hand. It is therefore in order to review the X-ray observations in this region and to suggest ways in which measurements at X-ray wavelengths may shed light on the physics of supernova remnants and the properties of the interstellar medium.

Three distinct X-ray sources have been discovered to date in the $\sim$40° diameter region termed the Gum Nebula. The first found was labelled Vel XR-1 by its discoverers (Chodil et al. 1967) and is now located by the Uhuru satellite at $9^h\ 00^m\ 27^s \pm 15^s$, $-40°\ 22' \pm 4'$ with the new designation 1ASE 0900-40 (Kellogg 1971). This object appears as a point source of 3 to 11 keV X-rays with an intensity $\sim$0.4 photon cm^{-2} sec^{-1}. There is no evidence to associate this source with the Vela supernova remnant.

Also coincidentally close in position to the Vela X radio and optical object is the X-ray source found by Palmieri et al. (1971) and identified with the Puppis A nonthermal radio source. This object is classed as a supernova remnant by Harris (1961) who suggests a distance of 1400 pc, much farther than the Vela X remnant. The low-energy cutoff observed by Seward et al. (1971) in the Pup A X-ray spectrum indicates an average gas density along the line of sight to the source to 0.14 to 0.5 atoms cm^{-3} if the distance is 1400 pc. The Puppis A radio shell is about 1° in diameter. Seward et al. find the associated X-ray source to be $\lesssim 0.^\circ5$.

The X-ray object of principal interest here is the strong soft source Vel XR-2 first observed by Grader et al. (1970). The location coincides with the extended radio source Vela X, which includes the pulsar PSR 0833-45, and with a network of fine optical filaments (catalogued Stromlo 16) which are seen in the emission lines of O^{++}, O^{+} and H (Milne 1968). The radio spectrum, the high degree of radio polarization, the indications of collisionally excited gas and the presence of a young pulsar all point to an identification of the 5° diameter region as a supernova remnant.

Energetically, the remnant is primarily, like the Crab nebula, an X-ray object. The X-ray emission from 150 eV to 2 keV corresponds to about 2.3×10^{35} erg sec^{-1} (Seward et al. 1971). It is evidently the brightest object in the night sky for 150 eV $< E <$ 500 eV.

According to the LRL study (Seward et al. 1971) the angular size of the X-ray emitting region is smaller at 0.2 to 0.3 keV than at 0.3 to 2 keV. Referring to Figure 1, the brightest filaments form a D shape which Milne (1968a) suggested was formed by a non-uniform radial expansion. 90% of the Vela X radio emission occurs within this D region, which includes the pulsar, while the LRL group reports the lower energy X-ray emitting region borders the D to the east. The higher energy X-rays, on the other hand, appear to come from a larger area consistent with the circle formed by completing the D. These authors suggest that there may be obscured filaments forming the rest of a shell. Support for this suggestion is seen in a diminished star count on the east side of the filaments approaching the galactic equator. As in the case of the Cygnus Loop, there is some indication that the X-ray emission is correlated with the optically bright, sharp filaments.

The associated pulsar PSR 0833-45 has not been clearly identified in either the optical spectrum or X-ray spectrum. A search for pulsed X-ray emission has led to upper limits for the fraction of the 0.15 to 2 keV flux contained in a pulse of 2.4% from Wisconsin data and 1% from LRL data, taken May 29, 1970 and May 13, 1970 respectively. Pacini and Rees (1970) have shown that if the high energy (optical and X-ray) emission from pulsars comes from synchrotron radiation at the speed of light circle, then the power radiated may vary as $(\text{Period})^{-6}$. In this case, by comparison with the Crab pulsar NP 0532, detection of the Vela pulsar in X-rays must await experiment sensitivities of 10^{-3} photon cm^{-2} sec^{-1}.

The analysis of spectra obtained by proportional counters is complicated by the fact that these detectors have a complex response function. The usual procedure is to fit models to the data which may have a physically meaningful interpretation and which make use of a number of free parameters consistent with the quality of the data. X-ray spectra of Vel XR-2 have been obtained by the LRL group (Palmieri et al. 1971, Seward et al. 1971) and by the Wisconsin group (Bunner et al. 1971) using 3 types of models: (a) thermal bremsstrahlung with an input spectrum $(1/E)\, e^{-E/kT}$ photon cm^{-2} sec^{-1} keV^{-1}; (b) a power law spectrum $E^{-\alpha}$ photon cm^{-2} sec^{-1} keV^{-1}; and (c) an emission line spectrum, based on the predictions of Tucker and Koren (1971) for a collisionally excited plasma.

Each model also makes use of an additional parameter which relates to interstellar absorption. If the neutral atomic hydrogen column density along the line of sight is N_H atoms cm^{-2} with other elements present according to the abundance ratios chosen by Brown and Gould (1970), then the effective photoelectric cross-section per H atom at energy E is

$$\sigma_{eff}(E) = \frac{\sum_i N_i \sigma_i}{N_H} \tag{1}$$

and the optical depth at energy E is

$$\tau(E) = N_H \sigma_{eff}(E) \tag{2}$$

Table 1 summarizes the results of this model fitting including the parameter N_H.

It is important to emphasize that these models are little more than mathematical artifices since even if the radiation were entirely thermal it is unlikely that a single temperature could adequately represent a region 40 pc in diameter. Figure 2 shows the spectrum of the Vela X remnant from radio, optical and X-ray data. The radio are from Milne (1968a), the optical point is based on emission measurements on filaments (Milne 1968b), and the X-ray sector is drawn for a 3.3 index power law without absorption for illustrative purposes.

However, regardless of the choice of model above, the observed pulse height spectra indicate a mass of absorbing gas along the line of sight equivalent to the "standard" interstellar gas of Brown and Gould (1970) containing 2.4 to 5.6 $\times 10^{20}$ hydrogen atoms per cm^2 (about one optical depth at 270 eV). The X-ray absorption measurement actually determines the concentration of elements heavier than hydrogen because of the strong dependence of the photoelectric cross-section on Z. At 270 eV, assuming Brown and Gould composition, the optical depth is 69% due to He and 26% to H. Above 526 eV, oxygen is the principal contributor. In principle, provided a reasonably well-established source spectrum is available, the X-ray absorption measurements allow a determination of the elemental and ionic composition along the line of sight to a source. This technique has been used recently to study the interstellar gas along the path to the Crab Nebula (Coleman et al. 1971).

For Vel XR-2, neither the source spectrum nor the observed pulse height distribution are known with the accuracy necessary for a detailed analysis. However, the estimate above is sufficient to place some constraints on models for the line of sight to the X-ray source. It is unlikely that any absorption occurs within or near the filamentary nebula itself. Milne (1968a) estimates the mass swept up by the expanding nebula at 30 to 170 $M_\odot$; therefore, if the diameter is 40 pc, an upper limit to the column density within the nebula is 0.15

Table 1
Spectral Models of Vel XR-2

Reference	Thermal without emission lines		Power law		Thermal with emission lines	
	kT	10^{-20} N_H	α	10^{-20} N_H	10^6 T	10^{-20} N_H
	keV	H-atoms cm^{-2}	–	H-atoms cm^{-2}	°K	H-atoms cm^{-2}
Palmieri <u>et al.</u> 1971	0.2 ± 0.14	2.4 ± 0.8	2 ± 1.2	5.6 ± 1	–	–
Seward <u>et al.</u> 1971	$0.23^{+0.07}_{-0.03}$	2.5 ± 1.2	4.2 ± 0.5	5.6 ± 2.5	–	–
Bunner <u>et al.</u> 1971	0.27 ± 0.03	3.6 ± 0.5	3.3 ± 0.5	4.0 ± 1	2 ± 1	4 ± 1

H-atom cm^{-2}. If the distance is 500 ± 100 parsecs, the line of sight is completely within our local spiral arm and the X-ray absorption indicates an average density of 0.24 ± 0.10 atom cm^{-2}, in agreement with the model of Brandt et al. (1971) and Alexander et al. (1971). A density as high as 0.4 protons cm^{-2} could be accommodated if a large fraction of the line of sight is at a temperature of 50,000 °K, as suggested by Alexander et al. (1971), since hydrogen is transparent to X-rays for $T > 15,000$ °K and He^{+} is semi-transparent (30,000 °K < T < 80,000 °K). Above 80,000 °K the effective cross-section drops drastically and the observed absorption would be difficult to explain.

By way of comparison with radio observations, a search for the 21-cm absorption line in the continuum radiation of PSR 0833-45 by Gordon and Gordon (1970) has yielded an upper limit of τ(21 cm) < 0.08. These authors conclude that either the line of sight to this pulsar is unusually lacking in cool hydrogen, or that whatever hydrogen is present must be sufficiently clumped that the line of sight happens to miss all such cool clouds. Evidence for the existence of such clouds comes from a study of several pulsar neutral hydrogen absorption measurements, in which a gap is found between the smallest 21-cm optical depth detected and upper limits set on others (Gordon et al. 1969). In contrast to the X-ray absorption measurement, which averages over a beam 5° in diameter, the pulsar measurement is a truly stellar line of sight and so has a higher probability of missing all clouds. Therefore the radio observations are not inconsistent either with the X-ray data or with the model of Brandt et al. (1971).

Refined X-ray measurements with thin window proportional counters and/or Bragg spectrometers will allow better estimates of the line of sight parameters. An observation of X-ray polarization would establish the emission mechanism as synchrotron radiation, but such measurements are extremely difficult for $\lambda > 6$ Å. The most promising attack will be the search for X-ray emission lines. If the X-rays are from a hot plasma at 2 to 3 × 10^6 °K, the lines of Fe^{15+} at 227 eV, Si^{9+} at 245 ev and O^{7+} at 652 eV, among others, should be prominent (Tucker and Koren 1971). A clear identification of even one emission line would establish a temperature reasonably well. Failure to observe lines with higher resolution devices will support synchrotron radiation as the source.

It is interesting to consider the possibility that emission lines may be found from a diffuse region surrounding the supernova remnant: If a large quantity of heavy element enriched material is ejected in the supernova outburst at energies above 10 MeV/nucleon, as suggested by Ramaty et al. (1971), these stripped nuclei may be carried beyond the remnant proper before slowing down to velocities at which electrons can be captured into excited states with subsequent K and L characteristic line emission.

In this connection, it should be mentioned that a systematic survey of the diffuse soft X-ray background in the $\sim 40°$ diameter Gum Nebula region has not yet been published. Both spectral features and spatial structure are of interest in this respect.

Including Vela X and Puppis A, the number of plausible identifications of X-ray sources with supernova remnants now reaches 16 (Table 2). Of these, Cep XR-3 and Oph XR-1 have not been confirmed as X-ray sources since they were reported in 1964-67. However, it would seem that it is yet too early to conclude that a majority of X-ray sources are not associated with supernovae.

That the 3 sources discovered to date which are strong sources below 1 keV, Vel XR-2, Pup A and the Cygnus Loop, all correspond to supernova remnants with relatively large angular diameters may be largely a reflection of their proximity to the sun and corresponding low interstellar attenuation. It is also possible, as Palmieri et al. (1971) suggest, that the soft spectra are an indication of age and that a steepening of the power-law index results from a decay of the high-energy electrons in the remnant. Alternatively, if the X-ray emission is thermal, the effect could indicate deceleration of shock waves leading to a decrease of effective temperature with age. A search for further very soft X-ray sources may lead to other large diameter remnants in this age class.

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Table 2

Supernova Remnants as X-Ray Sources

Supernova Remnant	X-Ray Source	Position Error	Distance (pc)	Age (yr)	X-Ray Power (10^{36} erg/sec)	Ref.
Crab 1054	Tau X-1	–	1700	917	10	
Vela X	Vel XR-2	–	460	11,000	0.23	1, 4
Puppis A	Pup A	0°.3	1200-1400		2.6	1, 17
Cygnus Loop	Cyg X-5	–	770	50,000	1.0	10, 12
Tycho 1572	Cep XR-1	0.2	3500	399	1.4	2, 7, 13
Cas A	Cas XR-1	–	3400	260	2.8	13, 17
CTA 1	Cep XR-3	1.1	1000-2000		0.9	2, 3, 9
P1439-62	Cen XR-1	1.5	2000-2300		1.3	2, 9
P1548-55	Nor XR-2	1.8	1600-3200		3.9	2, 9, 14
P1613-50	Nor XR-1	1.7	4300-5700		27	2, 9, 14
W28	Sgr XR-3/GX9+1	1.8	1300-1500		1.0	2, 6, 9, 15
3C392	3C392	0.2	1500-1600		0.4	2, 8, 9
3C396	3C396	0.5	1800		0.6	8, 9
13S6A (SN of 185 ?)	Cen XR-2 (UAT)	0°.6 in ℓ^{II}	2300-5300	1786 ?	Flared in 1967	2, 9, 11, 16
Kepler 1604	Oph XR-1	1.5	5300-10,000	367		2, 3
Milne 56	GX5-1	0.2	2400		10	5, 6, 9

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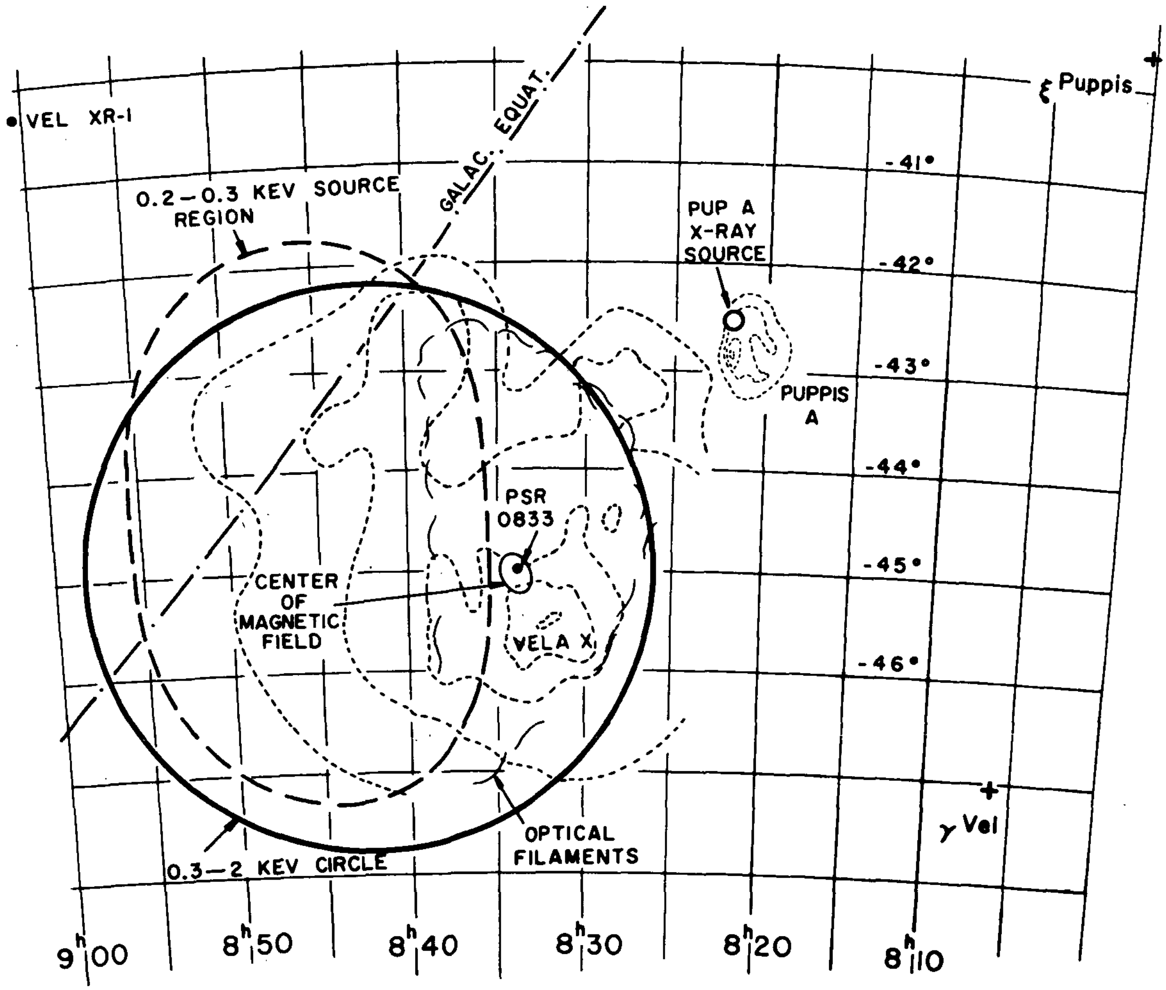

Figure 1. A map of the Vela-Puppis region. The radio brightness contours are 2650 MHz isotherms from Milne (1968a) and from Milne and Hill (1969). The X-ray source positions of LRL and ASE are shown. The large solid circle is a shell model used to fit the Vel XR-2 0.3 – 2 keV data of Seward et al. (1971). The dashed ellipse indicates the 0.2 – 0.3 keV emission. The accuracy of the location of the X-ray source Pup A is 0°.3. Also shown is the center of a circumferential magnetic field pattern (Milne 1968a), the location of the pulsar PSR 0833-45 and the optical filaments (wispy lines).

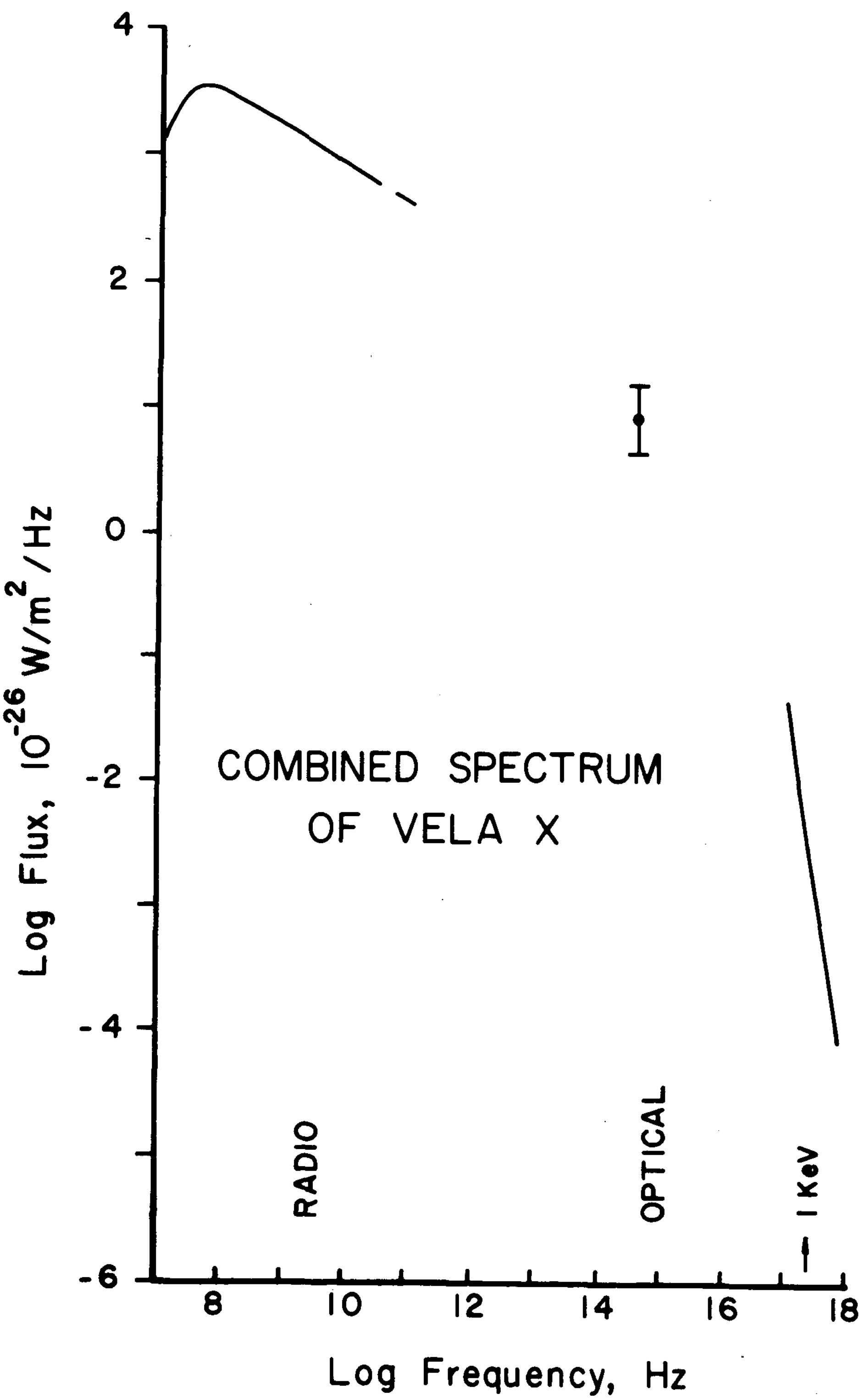

Figure 2. The spectrum of the Vela X remnant from radio frequencies to X-ray frequencies.