The Gum Nebula —A new kind of astronomical object

Did radiation from a supernova explosion ionize this huge mass of hydrogen? Four theories propose ways that the Nebula could have been created by energy from the supernova.

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The Gum Nebula is seen on photographs of the southern skies as an extensive region of ionized hydrogen that surrounds the well known Vela X supernova remnant. One of the largest objects in our galaxy, the Nebula was first recognized as a single emission complex by Colin S. Gum during the 1950's.[1] Until recently, astronomers assumed that it was a "Strömgren sphere," excited by ultraviolet light from the hot stars gamma Velorum and zeta Puppis within it. This excitation process accounts for the Orion Nebula and other H-II regions. The synchrotron and thermal bremsstrahlung mechanisms account for the radiation from supernova remnants, such as the Crab Nebula and Vela X; these objects consist of rapidly expanding matter ejected by the supernova explosions.

Some of us now propose[2] a different model for the origin of the Gum Nebula, because it appears to be too large (720 parsecs diameter, where 1 parsec is 3.26 light years) and too massive (180 000 solar masses, where 1 solar mass is 1.989 $\times 10^{33}$ grams) to have been ionized by the hot stars in its interior, or to be the remnant matter of an exploded star. We believe it to be a previously unrecognized class of galactic object, whose gases were ionized by ultraviolet radiation from the same supernova explosion that produced the Vela X remnant and the pulsar PSR 0833-45 that lies within the remnant. Because, in our model, the Gum Nebula was ionized by a star that no longer exists, we call it a "fossil Strömgren sphere." (See reference 3 for details of FSS observations and theories.)

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How did we come up with the "FSS" model? How do the theorists account for it? Do other, similar nebulas exist in our galaxy? How long can an ionized region such as the Gum Nebula persist in the absence of a significant energy source before its ions recombine and it merges indistinguishably into the interstellar medium?

Why a fossil sphere?

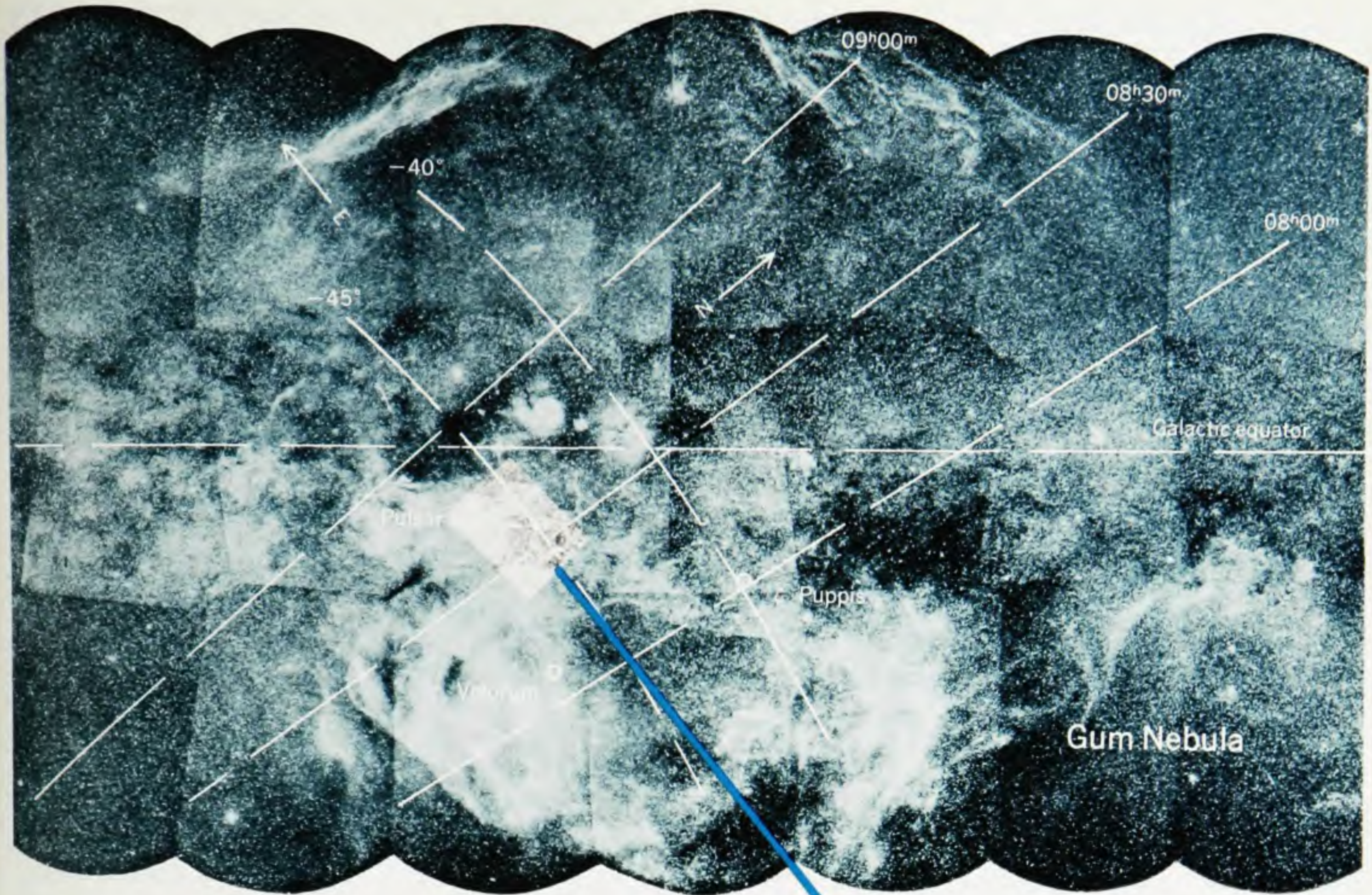
Our FSS model for the Gum Nebula, given in Table 1, is based on a variety of astronomical data. A young star cluster, called a "B-association," and the Vela X remnant are both located in the central region of the Nebula, and observations of both objects support the estimated distance to the region, 460 parsecs. The column density of electrons (total number of electrons per cm^2 in the line of sight) is revealed by the dispersion of pulsar radio signals, that is, by the wavelength dependence of pulse arrival times. This quantity leads to the mean electron density in the Nebula, 0.18 cm^{-3}. The rms electron density is inferred from the surface brightnesses of various parts of the Nebula, measured in the Balmer-alpha recombination line of hydrogen. The electron temperature is calculated from observations by the Radio Astronomy Explorer-1 satellite, which show that the hot nebular plasma is absorbing the background synchrotron radiation of the galaxy.

Our model's most controversial feature may be the diameter D of 720 parsecs, which corresponds to about 90 deg on the celestial sphere. The value, however, comes directly from

$$L + D/2 = 460 \text{ parsecs}$$

Here 460 parsecs is the observed distance to the nebular center, and L, the path length through the neutral gas between the solar system and the Nebula's edge, is found from observations of the interstellar neutral hydrogen in the ultraviolet and at 21 cm.

The value of 720 parsecs alarms observers[4] who find much of the nebular emission confined to a 35-deg-diameter zone on sky photographs (which show the nebular Balmer-alpha emission) with only a few scattered fragments more than 40 deg from the center. The confusion here is due to the invisibility

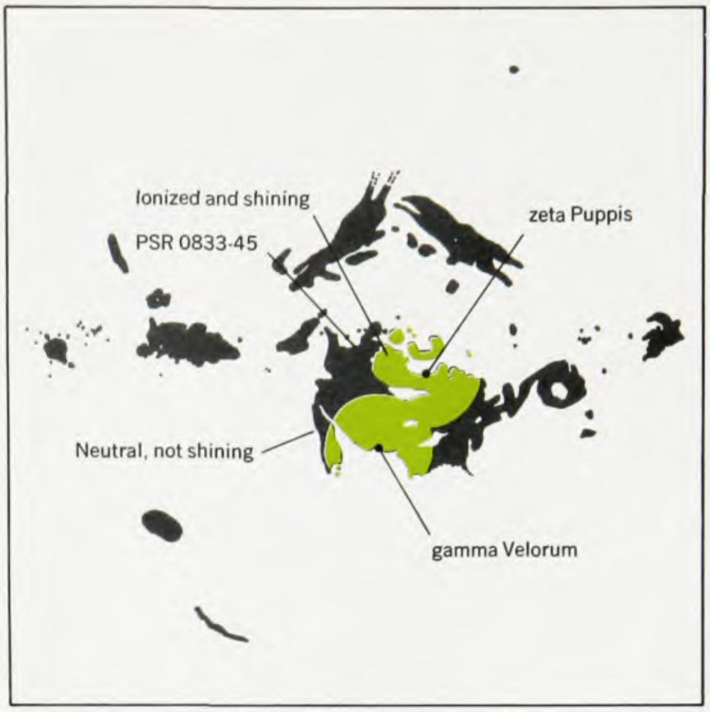


of most of the Gum Nebula on these photos, which show only the locally denser regions. The bulk of the gas is hot, tenuous and fully ionized. Significant Balmer-alpha radiation comes only with recombination, and for electron densities N_e less than or equal to one per cm^3, as in our model, the recombination time is at least 100 000 years, much longer than the time elapsed since the supernova ionized the Nebula.

The line of sight from the solar system to the center of the Gum Nebula lies in the galactic plane, a circumstance that allows us to deduce the nebular dimension in that plane. The extent of the Nebula at right angles to the plane is not determined by the observations. However, allowing for the well established general decrease of the interstellar gas density with distance from the galactic plane, we can represent the Nebula, for energy-argument purposes, as a cylinder with mean density 0.18 electrons per cm^3, diameter 720 parsecs, and height 100 parsecs.

If we now count the total number of electrons in the Gum Nebula and estimate the total energy E_{ph} of the ionizing photons that were needed to liberate the electrons from hydrogen atoms, we find E_{ph} is about 5×10^{51} ergs. The hot stars zeta Puppis and gamma Velorum can account for only a small part of this energy; the magnitude of E_{ph} suggests a supernova as the only adequate source. The observation of a supernova rem-

Gum Nebula appears in Balmer-α recombination–emission mosaic (top) as an extensive region of ionized hydrogen surrounding the Vela X supernova remnant (within rectangle). Mosaic photos were taken at Mount Stromlo Observatory, Australia.[15] Fossil Strömgren sphere theory says the Nebula was ionized about 11 000 years ago by the same supernova that left Vela X, seen here (bottom) in blue-light photo taken by Bart Bok (Arizona) at the Cerro Tololo Inter-American Observatory, Chile.



nant, Vela X, near the center of the Gum Nebula is thus highly suggestive.

Vela X, like the Gum Nebula, has been extensively studied only in recent years. In the late 1960's, Douglas Milne surveyed it with the 210-foot antenna at Parkes, New South Wales.[5] He classified it as a supernova remnant on the basis of its annular structure and polarized, nonthermal radio emission. Recent rocket measurements[6] show that the remnant is also a strong source of soft x rays (0.2–2 keV).

Also in the late 1960's, the search for pulsars led to the discovery[7] of PSR 0833-45, located in Vela X. It was the first case found of a pulsar in a supernova remnant and lent strong support to the idea that pulsars were neutron stars, formed in supernova events. The precisely timed slow-down rate of the PSR 0833-45 pulses implies that the object was formed about 11 000 years ago.[8] This value is consistent with a lower limit of 10 000 years for the age of the remnant, as deduced by Sidney van den Bergh[3] from the lack of detectable motion of the Vela X filaments on sky photographs taken some years apart.

The observations of Vela X and PSR 0833-45 show that a supernova, needed to account for the ionization of the Gum Nebula, did indeed occur within the Nebula, and it occurred much less than one nebular recombination time ago. Further, the soft x rays emitted by the remnant are an important clue to the precise ionization mechanism for the Gum Nebula, according to a leading theory that we shall discuss.

How was the Gum Nebula ionized?

Theoretical work on FSS has focused on two problems: "How is the energy released?" and "How does a FSS grow?" If the ionization is due to photons, then the answers to the two questions are probably not inextricably coupled, at least for times $t > \tau_1$, where τ_1 is the duration of the ionizing event. Thus, theories for the evolution of the Gum Nebula have been developed independently of the theories for its origin.

Four mechanisms for the ionization of the Gum Nebula by energy derived from the supernova have been suggested. They involve fluorescence of the supernova surroundings, which results in reemission of the He-II 304-Å radiation (Philip Morrison and Leo Sartori), radiation from a blast wave (Wallace Tucker), copious ultraviolet emission by the newly formed pulsar (A.G.W. Cameron) and ionization by particles (Reuven Ramaty, Elihu Boldt, Stirling Colgate and Joseph Silk). The box on page 45 illustrates the theories schematically; the relative sizes of the four sketches do not imply relative scale in the models.

Before we postulated our model for the Gum Nebula, Morrison and Sartori had tried to reproduce theoretically the observed visible-light behavior of supernovas.[9] They suggested that a supernova is surrounded by a zone of ionized helium (He^+), ejected during the prior evolution of the star, and they attributed the visible-light emission to fluorescence of the helium. The fluorescence process, excited by hard ultraviolet photons from the explosion, would also lead to strong emission of the 304-Å line of He^+, constituting a delta-function ultraviolet spectrum for ionizing the surroundings.

The Morrison–Sartori theory requires the emission of 10^{52} ergs in photons by the supernova explosion. However, a hydrodynamic analysis of the explosion rules out this much energy in photons, according to Colgate.[3] In addition, the fluorescence theory was derived in a rather *ad hoc* manner. Its chief merit thus lies in its prediction of FSS before the first one was discovered. We are reminded of George Gamow's modest remark, when he was congratulated on the discovery of the cosmic background radiation that he had predicted long before: "If I have lost a nickel and you have found one, it may not be the same nickel, but the coincidence is remarkable!" Gamow apparently finished "in the money," but the odds may be less favorable for the fluorescence theory; others are advancing alternatives.

A particularly compelling model has been proposed by Tucker.[10] According to him, the Gum Nebula was ionized by ultraviolet photons from a shock generated by the passage of supernova ejecta through the interstellar gas. The Vela X filaments are then the present visible manifestation of the shock. The observed soft x rays from the remnant are similarly attributed to the shocked region, which emits them at the rate

$$I = 3 \times 10^{56} N^2 R_S^3 P \text{ erg sec}^{-1}$$

The shock radius R_S is known from Milne's observations, N is the ambient gas density in cm^{-3}, and P is the temperature-dependent emissivity. When this equation is fitted to the rocket x-ray measurements, the temperature in the shock is found to be in the 0.4–4 $\times 10^6$ K range. Taking the lower value, Tucker finds that the output of the shock plasma in ultraviolet photons over the age of the supernova remnant has been about 10^{51} ergs.

Thus, according to the shock-wave model, the ionization of the Gum Nebula results from the efficient conversion

Before and after. Artist's conception shows denser portions of the interstellar hydrogen that forms the Gum Nebula. Before the supernova explosion (left), most of the gas is neutral (gray), and only the region near the two hot stars is ionized and shining (color). After the supernova explosion (right) the previously neutral gas is ionized and shining. Drawing is based on hydrogen Balmer-alpha map of Hugh M. Johnson and is not corrected for dust clouds and small background nebulas near the galactic plane.

of mechanical to radiative energy, and the release of ionizing photons by the shock is still underway.

Cameron favors yet another source of ionizing photons. He postulates intense ultraviolet emission by the pulsar in Vela X during the first year or two after its formation.[3] These photons, emitted in a narrow cone by the pulsar, would be scattered in all directions by electrons in the expanding remnant. Unlike the other theories for FSS, this one has not yet been worked out in detail.

Colgate[3] has calculated the velocity and particle mass distributions of supernova ejecta, and Ramaty, Boldt, Colgate and Silk use these results in their Gum Nebula theory.[11] They believe that the Nebula, or at least its denser regions in which N_e is 10 cm^{-3} or more, is ionized and heated by low-energy cosmic rays from the supernova. This process requires nuclei heavier than about carbon 12, and is thus consistent with Colgate's prediction that the bulk of the ejecta will be the products of silicon burning, with masses ranging up to that of iron. Presumably these particles are not predominant in cosmic rays at the Earth because their energy is expended in the interstellar gas.

In addition to the interaction of the low-energy cosmic rays with the nebular matter, the propagation of the particles is affected by the galactic magnetic field. It remains to be proven that the particles can have traversed the radius of the Gum Nebula in the available time of about 11 000 years. The particle model also requires at least twice as much energy in particles as the preceding theories require in photons, because a particle energy of 36 eV is needed to produce one ion pair in hydrogen. In any case, if significant amounts of the soft cosmic rays are moving through the denser clouds of the Gum Nebula, gamma-ray lines such as the 1.78-, 4.43- and 6.14-MeV transitions of silicon 28, carbon 12 and oxygen 16 should be detectable with the improved energy resolution of future satellite-borne instruments. Thus space experiments will provide a crucial test of this theory.

Evolution of FSS

Astronomers believe that the rate of supernova outbursts in the Galaxy is in the range of one per 25 to 100 years. Ultraviolet radiation from these events will penetrate to various distances, depending on the density distributions of the gas in the vicinity of the supernovas. Last year, a group at Harvard[12] estimated that once every million years a given point in the galactic disc will be exposed to ionizing photons from a supernova. They noted that, because the recombination time in the cool interstellar medium is typically about 3×10^6 years, the general excitation of the medium could be attributed to ancient supernova bursts. The mean time between exposures to ionizing radiation from hot stars (spectral class O) is, on the other hand, roughly 10^7 years.

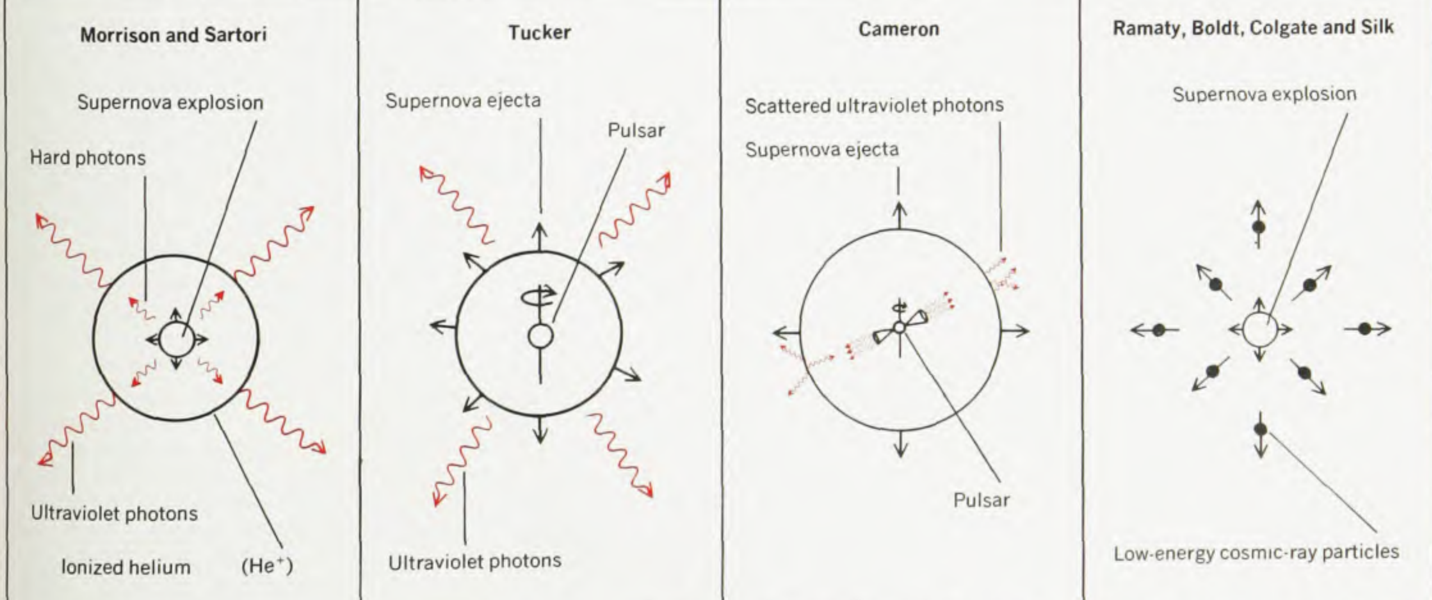
Now the Harvard group, according to a report by Richard McCray and Joseph Schwarz,[3] have calculated the physical development of fossil Strömgren spheres on time scales ranging up to 10^6 years. They have assumed ionization by ultraviolet photons from an optically thin bremsstrahlung source, which resembles the continuum radiation spectrum in Tucker's model but neglects the contribution of emission lines. Their results are shown in the box on page 46. Fractional ionization $x = N_e/(N_H + N_{H+})$ is given, together with the temperature, for the zone within a radius R_1 that is fully ionized when the FSS is created, and for locations at $2R_1$ and $3R_1$.

For a given supernova, the radii are calibrated from the relation

$$R_1 \approx 70\,(E_{51}/N_H)^{1/3} \text{ parsecs}$$

Here N_H is the neutral hydrogen density in cm^{-3} before the supernova explosion

Gum Nebula energy-source theories



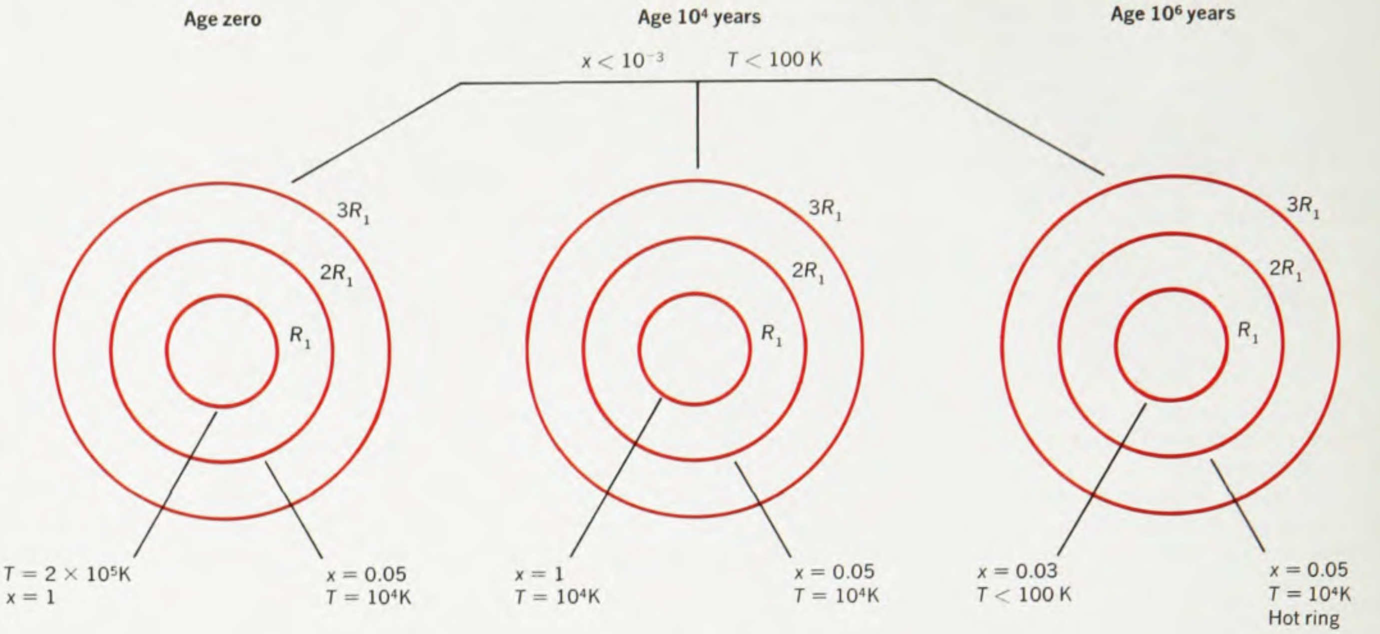
Morrison and Sartori: Hard photons from supernova explosion cause ionized helium shell to fluoresce, emitting longer-wavelength ultraviolet photons.

Tucker: Ultraviolet photons are emitted from the shock wave that is generated when ejecta from the supernova move through the interstellar gas.

Cameron: Young pulsar emits ultraviolet photons, which are scattered by electrons in the exploding, still optically thick, supernova shell.

Ramaty, Boldt, Colgate and Silk: Energy is provided by low-energy cosmic-ray particles that come from supernova explosion.

Evolution of a fossil Strömgren sphere



According to this model, due to Richard McCray and Joseph Schwarz, the result after a million years have passed is a hot zone at $2R_1$ (R_1 is the radius of the zone that is fully ionized at age zero) and a cool center. Here x, the "fractional ionization," is the ratio $N_e / (N_H + N_{H^+})$.

occurs, and E_{51} is the energy in ionizing photons (units of 10^{51} ergs). For 100 K $< T <$ 10 000 K, the fully ionized region cools faster than the zone at $2R_1$, and the result after a million years have passed is a hot zone at $2R_1$ and a cool center. Of course, about that time on the average, another supernova explodes in the vicinity, and the ionization of the region is enhanced again.

McCray and Schwarz also predict the formation of condensations within FSS, with various characteristic sizes. These condensations result from thermal instabilities in the gas. The most interesting case is for an FSS age of about 10^6 years and a local temperature of less than 10^4 K, when condensations with typical dimensions of 1–100 parsecs are likely to occur. If the denser of these condensations can cool to about 30 K without fragmenting, they may become self-gravitating and eventually form stars. Conceivably, the death of a star in a supernova explosion may ultimately trigger the birth of other stars.

Are there other FSS?

We have learned a great deal from the Crab Nebula, one of the first identified cosmic sources of radio and x-ray emission, the first natural object in which synchrotron radiation was recognized and the site of the only known optical pulsar. By the same token, we are always conscious of its uniqueness. The Gum Nebula may have given us our only reliable estimate for the radiative energy loss of a supernova. But is this FSS, with its vast energy content, also unique?

The possibility that FSS surround several young supernova remnants has been investigated. These include the Crab, Tycho and Cassiopeia A remnants, all of which are more distant than Vela X. They are still so young that appreciable recombination in their surrounding FSS is not expected, and we would not expect to see their Balmer lines. Minas Kafatos and Morrison[13] have studied the case of Tycho. They find that the 4959- and 5007-Å radiation, corresponding to forbidden transitions of doubly ionized oxygen, may be detectable in the denser condensations of the FSS. Because it is well off the galactic plane and substantially more obscured than Vela X, the Crab remnant appears to be a poor target for an FSS search. Manuel Peimbert and van den Bergh have studied a faint nebula that appears to surround the heavily obscured, roughly 300-year-old Cassiopeia A remnant.[14] Balmer-alpha emission is observed, and their analysis, which takes only this radiation into account, yields 10^{50} ergs as the energy required to ionize this possible FSS.

A different approach may also be fruitful in the search for FSS. Rather than concentrate on the known young supernova remnants, we can check the

Gum Nebula Model (Alexander, Brandt, Maran and Stecher)

Parameter	Value	Relevant observations
Distance to central region	460 parsecs	Photometry of stars; optical and radio brightness distributions of Vela X.
Diameter in the galactic plane	720 parsecs	Interstellar Lyman-alpha absorption; 21-cm measurements of neutral hydrogen in the solar vicinity; scattering of solar Lyman-alpha radiation by nearby interstellar hydrogen; nebular distance
Mean electron density ($\langle N_e \rangle$)	0.18 cm^{-3}	Pulsar dispersion measures
rms electron density ($N_{e(rms)}$)	1.3 cm^{-3}	H-alpha emission measures
Clumping factor	60	$= (N_{e(rms)})^2 / \langle N_e \rangle^2$
Electron temperature	$\geq 5.7 \times 10^4$ K	Absorption of 4-MHz background radiation

sky for objects that resemble the Gum Nebula. This technique has led to several candidates. Hugh Johnson[3] has suggested a complex of emission nebulas in Cygnus, with a diameter of about 45 deg. Thomas Matthews and Christian Simonson[3] call attention to a smaller Cygnus system, with a diameter of about 17 deg. They propose the supernova that gave rise to remnant G78.2 + 1.8 as the ionization source, although they are unable to exclude the possibility of ionization by hot stars.

William J. Webster[3] has considered the large complexes Orion I, Cepheus IV and IC 1795–IC 1805–IC 1848. The evidence on these three regions does not really favor an FSS interpretation; they are better described as emission systems that are poorly understood. The relatively small distance of Vela X, its age of about 11 000 years, the relative lack of obscuration—all these factors make the Gum Nebula the most clearly recognizable, and probably the only well demonstrated, case of a fossil Strömgren sphere.

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