THE ASTROPHYSICAL JOURNAL, 230:713–716, 1979 June 15

AN UPPER LIMIT FOR THE TOTAL ENERGY OF RELATIVISTIC PARTICLES CONTAINED IN THE EARLY STAGES OF SUPERNOVA EXPLOSIONS

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Received 1978 August 1; accepted 1978 December 28

ABSTRACT

A model is proposed for the emission of X-rays from supernova explosions wherein the thermal distribution of photons from a supernova photosphere is inverse Compton scattered by relativistic electrons within or near the surface of the star. Using this model, upper limits for the number of relativistic electrons and their total energy are established on the basis of upper limits to the observed X-ray luminosity of a supernova during maximum light. These upper limits, in conjunction with radio frequency upper limits obtained by Brown and Marscher, strongly suggest that supernovae do not produce significant numbers of relativistic particles until at least 70 years after the initial outburst. This, in turn, implies that young supernovae cannot account for the radio and X-ray variability of active galactic nuclei and quasars.

Subject headings: galaxies: nuclei — quasars — stars: supernovae — X-rays: sources

I. INTRODUCTION

The question of the presence or absence of relativistic particles in supernova (SN) explosions has import for a number of current astrophysical problems, including cosmic ray production and the source of energy in active galactic nuclei. Colgate and Johnson (1960) have suggested that relativistic particles can be produced by a shock wave in the outermost layers of the expanding photosphere of a supernova explosion, while Gull (1973) and Chevalier, Robertson, and Scott (1976) have proposed that relativistic particles are produced much later as the supernova remnant interacts with the interstellar medium. Supernova explosions and other properties of supermassive stars have also been postulated as the source of energy for galactic nuclei and quasars (see, e.g., Ozernoy 1974; Colgate 1967; and references cited therein).

Recently, Brown and Marscher (1978) have published an extensive survey of radio observations of 46 young supernovae whose ages range from a few months to 79 years. In this survey, none of the supernovae were detected as radio sources at 11 and 3.7 cm (2.8 and 8.1 GHz) with a flux density $\leq$5–10 mJy. Marscher and Brown (1978), Goss *et al.* (1973), and Gottesman *et al.* (1972) do report a possible flare of radio emission from SN 1970g. If we ignore for now the possible association of radio emission in galactic nuclei with supernovae, the radio flare in SN 1970g represents the only radio detection of a supernova to date.

The conspicuous absence of early radio emission from events as energetic as supernovae, combined with the belief that supernovae are responsible for the production of cosmic rays in our Galaxy, suggest to Marscher and Brown that either the cosmic rays are accelerated sometime at least 75 years after the initial explosion, or that the magnetic field in young remnants evolves very slowly [$B(t) \approx t^{-1/2}$] in order that the Razin-Tsytovich effect suppress the synchrotron radiation from relativistic electrons. Failure to detect radio emission was generally thought to mean a magnetic field $B \lesssim 2 \times 10^{-3}$ gauss. Marscher and Brown suggest that the ambiguity between these two interpretations can be resolved by γ-ray observations of the supernova, which would detect collisions of the relativistic protons with ambient material, in that the resultant π^0 decays would produce detectable γ-ray fluxes if relativistic particles are present.

II. DISCUSSION

I suggest an alternative mechanism for the production of high-energy photons ($\nu \geq 10^{18}$ Hz), in a supernova explosion. Given the presence of relativistic particles within or near the expanding photosphere, the ambient, thermal protons will be inverse Compton scattered to produce X-rays. The lack of detection of such X-rays can be used to place upper limits on the energy contained in cosmic ray electrons created during the early stage of the outburst.

During a supernova explosion, we assume (following Falk and Arnett 1973, 1977) that the photosphere of the red giant star expands and eventually becomes optically thin. This transition appears to occur approximately 40 days after the explosion, and is marked by an apparent decrease in the effective radius of the photosphere. As a consequence of this transition, the energy density of the thermal photons in the expanding shell of material decreases.

Various authors have suggested that in diverse astrophysical settings relativistic particles can scatter ambient photons to produce X-rays or γ-rays (see, e.g., Felten and Morrison 1963; Hoyle 1965; Gould 1965; Jones 1968; Jones, O'Dell, and Stein 1974). If the relativistic particles are present within or near the supernova photosphere as Marscher and Brown (1978) suggest, the thermal photons may be inverse Compton scattered to produce X-rays. The assumption of a distribution of relativistic particles thoroughly mixed with the supernova photosphere is not a critical one. In their work on supernova explosions, Falk and Arnett (1977) suggest that the expanding photosphere may fragment into optically thick "blobs" due to Rayleigh-Taylor instabilities. Chevalier and Klein (1978) also show extensive fragmentation of the expanding photosphere during a supernova explosion. The energy density of the thermal photons within the interstices may be roughly equal to the energy density of an unfragmented photosphere. In this case also, relativistic electrons contained within the interstices would radiate by the inverse Compton mechanism.

To determine what limits this model implies for the energy contained in relativistic electrons, we must calculate the expected X-ray luminosity and compare that to the upper limits established by various observers. The most stringent constraints on the energy contained in relativistic particles are obtained by this method during the time shortly before and until 40 days after maximum light. Afterwards an estimate of the thermal photon energy density must be made by obtaining an optical depth for the expanding cloud of material.

For a distribution of thermal photons, the energy density is

$$u = \Omega a T^4 \equiv (1 - e^{-\tau_\nu}) a T^4 \,, \tag{1}$$

where τ_ν is the optical depth, T is the temperature of the photosphere, a is the first radiation constant, and Ω is a factor to account for a gray-body approximation. The factor Ω can also describe the energy density of thermal photons at some distance from an optically thick plasma, if we set

$$\Omega \approx (r_{\rm ph}/R)^2 \,, \tag{2}$$

where $r_{\rm ph}$ is the photospheric radius at a given time, and R is the radius within which the relativistic electrons are thought to be contained.

It is certainly true that the physical environment inside a star undergoing a supernova explosion is a matter of some speculation. Different theories present quite different pictures of the process, and the inverse Compton mechanism is somewhat dependent on the distributions of the photons and electrons which these models imply. If the electrons are accelerated within, or move through, the photosphere of the star, the usual inverse Compton calculations (which assume isotropy of the photon and electron distributions) apply. A case can be made for isotropy of the electron distribution within an expanding supernova photosphere. Marscher and Brown (1978) estimate that the magnetic field in SN 1970g can range from 10^{-2} to 1 gauss. For electrons with $\gamma \approx 10^2$, this implies an electron orbit with a radius of 10^7 to 10^5 cm. It is likely, therefore, that electrons will have an isotropic velocity distribution within or near the supernova photosphere. In the event that the electrons stream radially outward through the photosphere (which would imply the magnetic field $B = 0$ and no synchrotron emission) the inverse Compton mechanism would still produce significant X-ray flux, and upper limits for the total number of relativistic particles can be obtained on the basis of upper limits of X-ray observations of supernova.

Relativistic electrons may occupy the volume beyond the surface of the supernova photosphere. In this region, the assumption of an isotropic distribution of photons (and, possibly, of electrons) must be relaxed. Pacholczyk (1970) shows (eq. [5.41]) that the direction cosine for incident photons with respect to the relativistic electrons in the laboratory frame (the frame at rest with respect to the center of the star) is

$$\mu_i = 1 - \frac{E_f}{2\gamma^2 E_i} \,, \tag{3}$$

where E_f is the final energy of the inverse Compton scattered photon, γ is the ratio of the total electron energy to its rest mass ($E/m_e c^2$), and E_i is the incident photon energy. For forward scattering ($E_f = 4\gamma^2 E_i$), $\mu_i = -1$. Thus, μ_i takes on values from -1 to 1 in the laboratory frame. Clearly, if we were to restrict the acceptable values of μ_i (this would occur if the photon distribution were anisotropic in the laboratory frame), we would affect the maximum energy of the inverse Compton scattered photons. For a relativistic electron at a radius greater than the radius of the photosphere, the direction cosine, μ_i, can take values from 1 to $[1 - (r_{\rm ph}/R)^2]^{1/2}$, where $r_{\rm ph}$ is the photospheric radius, and R is the radial position of the relativistic electron. The maximum energy of the scattered photon then becomes

$$E_f = 2(1 - \mu_i)\gamma^2 E_i \,. \tag{4}$$

If the electron is at a radius 3 times that of the photosphere, then μ_i can have values ranging from 1 to $\sim$0.9 and the maximum energy E_f of an inverse Compton scattered photon is $\sim 0.1\gamma^2 E_i$. Therefore, to produce the same ratio of scattered photon energy to initial photon energy, we require electrons with somewhat higher γ's. Within or near the photosphere of a star, the aberration of starlight for a relativistic electron in the electron rest frame produces an almost unidirectional beam of photons for any incident direction in the laboratory frame except for $\mu_i = 1$. The increase in the required energy of the relativistic electrons may be thought of, therefore, as due to the redshift of photons which are traveling in the same direction as the scattering electrons.

Though a detailed calculation of the inverse Compton X-ray flux from an anisotropic distribution of electrons and/or photons is left to a subsequent paper, it is clear that even for relativistic electrons beyond the photospheric radius, and moving radially outward (the worst possible case for the process), a significant inverse Compton X-ray flux can result.

For the moment, we assume that the relativistic electrons are within the supernova photosphere. We can, therefore, modify equation (4-51) given by Tucker (1976) to derive an expression for the X-ray flux produced by a power-law distribution of relativistic particles $N(\gamma) = A\gamma^{-n}$ electrons cm^{-3} in the presence of a thermal photon distribution. If the thermal photons have an energy density as given by equation (1), then

$$F_\nu = \frac{L_\nu}{4\pi D^2} = \frac{4.2 \times 10^{-40}}{3D^2}\,\Omega R^3 A T^{3+q} b(n)\left(\frac{2.1 \times 10^{10}}{\nu}\right)^q \text{ ergs cm}^{-2}\text{ s}^{-1}\text{ Hz}^{-1}\,, \tag{5}$$

where D is the distance to the source, R is the source radius, A is the normalization constant of the power-law distribution of relativistic electrons, n is the spectral index for the electron number distribution, $b(n)$ is determined from the X-ray spectrum and depends only on n, γ is the ratio of the electron energy E to the rest mass $m_e c^2$, $q = (n-1)/2$ is a constant determined from the spectral index n of the X-ray power law spectrum (which we have assumed to be equal to the unsuppressed synchrotron power law spectral index), and ν is the frequency of the observed X-ray radiation.

The total X-ray luminosity between two frequencies ν_1 and ν_2 from a thermal photon distribution then becomes

$$L_{\text{X-ray}} = (4.2 \times 10^{-40})\frac{4\pi}{3} b(n)\Omega R^3 A T^{3+q}\int_{\nu_2}^{\nu_1}\left(\frac{2.1 \times 10^{10}}{\nu}\right)^q d\nu \tag{6}$$

and

$$L_{\text{X-ray}} = (2.94 \times 10^{-30})\Omega A R^3 T^{3.75}(\nu_2{}^{1/4} - \nu_1{}^{1/4})\text{ ergs s}^{-1}\,, \tag{7}$$

where we have assumed $n = 2.5$. Then $q = 0.75$, and $b(2.5) = 7.57$.

Sprott *et al.* (1974) observed SN 1971s in NGC 493 with the MIT OSO 7 detector, and obtained an upper limit for the total continuous X-ray luminosity of $L \leq 5 \times 10^{43}$ ergs s^{-1} from 1 to 5 keV. The upper limit for an X-ray pulse between 1 and 9 keV was 5×10^{48} ergs, assuming that the pulse has a duration of 2 s to 3 minutes. Sprott *et al.* also derive an upper limit of 80 Mpc for the distance to NGC 493. Using these values and taking $T = 5 \times 10^4$ K, we find the product of the volume R^3 and the normalization constant A to be

$$AR^3 = \frac{L_{1\text{-}5\,\text{keV}}}{1.35 \times 10^{-8}\Omega}\,. \tag{8}$$

The energy density in terms of relativistic electrons is

$$\epsilon = \gamma m_e c^2 N(\gamma) \approx m_e c^2 A\gamma^{-n+2}\,. \tag{9}$$

Assuming $\gamma \approx 10^2$, the total energy in terms of relativistic electrons then becomes

$$E_{\text{tot}} \approx \frac{4\pi}{3}R^3\epsilon = \frac{2.51 \times 10^1}{\Omega}L_{1\text{-}5\,\text{keV}}\text{ ergs}\,. \tag{10}$$

For $\Omega \approx 1$, the upper limit to the total energy in relativistic electrons is

$$E_{\text{tot}} \leq 1.26 \times 10^{45}\text{ ergs}\,.$$

This represents the maximum energy available in relativistic electrons for SN 1971s. For a pulse X-ray emission with a duration of 2 s, $E_{\text{tot}} \leq 4 \times 10^{49}$ ergs, and for a pulse of 3 minutes duration, $E_{\text{tot}} \leq 5 \times 10^{47}$ ergs. Using the same assumption about the source model, X-ray upper limits of SN 1967h 7 to 34 days after maximum light obtained by Bradt *et al.* (1968) yield an upper limit of

$$E_{\text{tot}} \lesssim 1.5 \times 10^{44}\text{ ergs}$$

as the total energy available in relativistic electrons.

To estimate the inverse Compton X-ray flux from electrons outside the star's photosphere, we note that an increase in the required electron energy to produce the final photon energy means a decreased number density of electrons. For $R \leq 3r_{\text{ph}}$, the maximum scattered energy is $E_f = 0.1\gamma^2 E_i$. For isotropic inverse Compton scattering, $E_f = 4\gamma^2 E_i$. Therefore, the electron in a particular scattering event must be a factor of $\sim$6 higher in energy to convert photons with initial energy E_i into final energy E_f. For a power law distribution of electrons previously assumed, this implies that the number of available electrons will decrease by approximately a factor of 10^{-2}. Therefore, the calculated X-ray flux will decrease by a factor of 10^{-2}, in addition to the decrease caused by the $1/r^2$ dependence of the photon energy density. We may safely estimate the upper limits, for the electron energy within a radius 3 times the radius of the photosphere, therefore, by reducing the expected X-ray flux by a factor of 10^3. Thus, for SN 1971s, the upper limit to the energy in relativistic electrons within a radius 3 times that of the photosphere is $E_{\rm tot} \lesssim 10^{48}$ ergs. For the case of SN 1967h, $E_{\rm tot} \leq 10^{47}$ ergs. If the typical energy release in a supernova explosion is on the order of 10^{51} ergs, the energy of relativistic electrons in the early stages of the explosion represents a negligible contribution to the total.

III. CONCLUSIONS

As the supernova photosphere expands, assuming $N_e \propto R^{-3}$ and $B \propto R^{-2}$, the maximum suppressed frequency decreases as R^{-1}, and the Razin-Tsytovich effect becomes negligible. Therefore, the time when suppression is most likely to occur corresponds to the time when the X-ray upper limits are most severe. Additionally, the X-ray upper limits are not dependent on the presence of a magnetic field. Though the data constitute only a limited sample, I make the plausible assumption that the 46 supernovae observed as upper limits by Marscher and Brown (1978) in the radio frequency range, and the various supernovae observed as upper limits in the X-ray frequencies are not atypical. If the radio and X-ray observations did not show evidence of detectable emission, it is because the supernovae did not produce significant numbers of relativistic particles from times very early in the initial explosion until times at least 70 years afterward. Consequently, unless the mechanism for supernova explosions in supermassive stars is very different from that of ordinary massive stars, multiple supernovae cannot be used to explain the radio and X-ray emission of galactic nuclei and quasars, which can brighten on time scales of days.

Continued measurements at radio, optical, and X-ray frequencies would be helpful in determining more exact limits on radio and X-ray production in supernova explosions. Measurements of possible correlations in the variability of radio, infrared, optical, ultraviolet, and X-ray emission from galactic nuclei would also be helpful in determining the mechanisms associated with energy production in that environment.

I thank S. Colgate, B. Dennis, J. Dolan, J. Felten, A. Marscher, T. Nagy, J. O'Keefe, W. Rose, and J. Scott for helpful discussions.

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