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X-RAYS FROM SUPERNOVA 1987A: BENEATH THE RADIOACTIVE LAYERS

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ABSTRACT

The detection of X-rays from SN 1987A is providing important information about the processes taking place in the early evolution of supernovae. In the energy range above 20 keV, down-Comptonization of γ-ray lines emitted by ^{56}Co represents a significant source of X-rays. If the emission is dominated by this process, a presence of 0.07 $M_\odot$ of ^{56}Co—as inferred from the bolometric light curve—entails that the hard X-ray flux should dramatically decrease around the end of 1988, independent of any assumption about the envelope structure.

The X-ray flux below 20 keV arises probably from a nonthermal nebula produced by a rotating neutron star. Such a nebula might contribute to the flux at high energies, and the relative importance of its contribution should become quantifiable after the complete decay of the radioactive material. We discuss the parameters of the nonthermal nebula and its expected evolution, the properties of the neutron star, and the nature of the short time scale variability observed in the soft X-rays.

Subject headings: gamma rays: general — radiation mechanisms — stars: individual (SN 1987A) — stars: neutron — stars: supernovae

I. INTRODUCTION

Common wisdom maintains that SN 1987A went up to expectations in most respects. In particular, a delayed X-ray emission had been predicted as the result of down-Comptonization of γ-ray lines from ^{56}Co (McCray, Shull, and Sutherland 1987; Xu *et al.* 1988), and indeed the instruments on board *Ginga* and *Mir-Kvant* have detected the supernova (Dotani *et al.* 1987; Sunyaev *et al.* 1987). The γ-ray lines themselves have been detected by *SMM* (Matz *et al.* 1988) and by several balloon experiments (Sandie *et al.* 1988; Mahoney *et al.* 1988; Gehrels *et al.* 1988).

However, the observed spectrum and light curve of the source do not match the early predictions. The X-rays appeared sooner than expected and have remained more or less at the same level over about one year, i.e., many *e*-folding times of ^{56}Co. This behavior contradicts the models based upon unmixed or "reasonably" mixed distributions of ^{56}Co and can be explained only if the radioactive material is arranged in a way such that the gradual unveiling of the interior compensates almost exactly the decay of the exposed nuclei. Furthermore, the radioactive model inherently entails a sharp cutoff below $\sim$20 keV because of photoelectric absorption. Observations show, however, that the spectrum continues to rise at least down to 6 keV (Dotani *et al.* 1987; Tanaka 1988). The low-energy emission appeared more or less simultaneously with the high-energy one and can be described by a power law with a similar index; at intermediate energies (20–30 keV) the spectrum shows a plateau or knee, so that the two spectra are misaligned.

In this paper wil will argue that the characteristics of SN 1987A can be understood if two mechanisms are simultaneously at work. They should be relevant above and, respectively, below a photon energy $\sim$20 keV; besides being the location of the expected cutoff, this energy also corresponds to the observed spectral feature, indeed suggestive of a physical discontinuity; in the following, we will refer to the two spectral regions as to the hard and soft X-rays, respectively.

A good candidate for the soft X-ray emission is synchrotron radiation from a nonthermal nebula, powered by a central neutron star. This can be detected if the envelope has undergone a process of early fragmentation, leading to the opening of transparent lines of sight towards the central region. Most of the hard X-ray flux can be provided by radioactivity, although some contribution from the pulsar nebula cannot be ruled out. In any case, synchrotron emission will dominate the entire spectrum in the near future, as soon as the radioactive decay will have eliminated completely the ^{56}Co.

In § II we discuss the high-energy emission and show that, if it remains at the measured level, and if it originates mainly from radioactive decay, one can establish a definite upper limit to its duration. In §§ III and IV we discuss the various possible ways of accounting for the low-energy emission and the properties of the pulsar nebula, respectively. In § V we present our conclusions.

II. HARD X-RAY EMISSION

According to the standard theory, the hard X-rays are born as γ-ray photons from radioactive ^{56}Co and are then degraded in energy as they diffuse outward by means of repeated Compton scatterings.

Prediscovery computations had all the ^{56}Co in a shell just above the neutron star surface and predicted a narrow peak in the light curve. This has been cured by moving a suitable amount of ^{56}Co closer to the envelope boundary, so as to account for the early appearance of the X-rays. Also, the flat top of the light curve has been reproduced by an ad hoc distribution of the radioactive material throughout the envelope (Pinto and Woosley 1988; Ebisuzaki and Shibazaki 1988).

We have, however, a direct handle on the distribution of ^{56}Co, involving no assumptions beside the self-similarity of the expansion. The γ-ray lines observed at 847 and 1238 keV provide at any given time a measure of the amount of ^{56}Co lying at a Thomson depth $\tau_{\rm Th}$ less than about 3 (because of the onset of relativistic effects, this value corresponds to a Klein-Nishina depth of about 1). By scaling the depth of a given layer as t^{-2}, it is possible to invert the γ-ray line light curve for the

^{56}Co distribution as a function of τ_{Th}, and then compute from there the hard X-ray light curve.

Computations along these lines (see also Shibazaki and Ebisuzaki 1988; Kumagai *et al.* 1988) show that both the hard X-rays and the γ-ray lines can be accounted for simultaneously. We must stress, though, that the standpoint is provided by the γ-ray lines, which are affected by large observational errors; so the correct statement is that a substantial fraction of the hard X-rays certainly is of a radioactive origin, but it cannot be excluded that a significant fraction is due to a different source. At the present stage, to attribute the entire hard X-ray emission to down-Comptonization is compatible with the data, but must be regarded as an extra assumption.

Once this assumption is made, the observations at a certain X-ray energy are a measure of the ^{56}Co at the corresponding τ_{Th}; again, it is possible to recover the distribution of ^{56}Co versus τ_{Th}, with the advantage of using as input the X-ray data, which are closely spaced in time and have relatively small errors.

Let $n(r, t)$ be the electron density, $R(t)$ the outer radius of the envelope, $x = r/R$, and ϵ a fiducial hard X-ray energy; then,

$$\tau_{Th} = \int_x^1 \sigma_{Th}\, nR\, dx = f(\epsilon)\ ; \qquad (1)$$

f is a function depending slightly on geometry, and mostly on the physics of Compton scattering: given the initial energy of the photon and the desired final energy ϵ, it measures the required number of scatterings in terms of a Thomson depth; the dependence on the initial photon energy is canceled by averaging over the various γ-ray lines. Equation (1) defines the comoving location of a photosphere, x, as a function of ϵ and t; by taking the partial derivatives we get

$$\frac{\partial x}{\partial \epsilon} = -\frac{f'}{\sigma_{Th}\, nR}\ ; \qquad (2)$$

$$\frac{\partial x}{\partial t} = -\frac{2f}{\sigma_{Th}\, nRt}\ ; \qquad (3)$$

where use has been made of the scaling $nR \propto t^{-2}$.

Define further $L(\epsilon)$ to be the X-ray differential photon luminosity of the supernova, q the relative (initial) abundance of ^{56}Co, y the photon yield per decay, and t_{Co} the radioactive cobalt e-folding time; we may write

$$L(\epsilon) = 4\pi R^3 nq \exp\left(\frac{-t}{t_{Co}}\right)\left(\frac{y}{t_{Co}}\right)x^2 \frac{\partial x}{\partial \epsilon}\ , \qquad (4)$$

and for the total (initial) amount of radioactive cobalt, N:

$$N = \int_t^{t_{in}} 4\pi R^3 nqx^2 \frac{\partial x}{\partial t}\, dt = \int_t^{t_{in}} \frac{2f}{f'} \frac{t_{Co}}{t} \frac{L}{y} \exp\left(\frac{t}{t_{Co}}\right) dt\ . \qquad (5)$$

Here the integration goes from the time t_{in} when X-rays of energy ϵ were first detected up to present, and gives only the fraction of N outside the present location of the photosphere $x(\epsilon)$.

We have tried two simple-minded approximations to $f(\epsilon)$:

$$f = \sqrt{mc^2/\epsilon}\ ; \quad f = \sqrt{(mc^2/\epsilon) - 1} + 3.4\ . \qquad (6)$$

Both of them assume that the first scattering brings the photon energy to mc^2, irrespective of the initial energy, and that the successive scatterings obey the nonrelativistic law; the Thomson depth required for the first scattering, however, is different in the two expressions, and is equal to 1 and 3.4, respectively (the latter value is an average of the Klein-Nishina corrections for the various ^{56}Co lines, weighted with the relevant branching ratios).

As a fiducial energy we have taken 40 keV, where the quantity $(2f/f')L(\epsilon)$ is maximum, and the requirement on N is tightest [L(40 keV) $= 1.0 \times 10^{-4}$ photons cm^{-2} s^{-1} keV^{-1}; Sunyaev *et al.* 1987]. Finally, we have integrated equation (5) up to the time t when N becomes equal to 0.07 $M_{\odot}$, the total amount of cobalt deduced from the bolometric light curve (Catchpole *et al.* 1988; Whitelock *et al.* 1988; Woosley 1988).

Using the approximations given in eq. (6), we find $t = 635$ and 550 days, corresponding to 1988 late November and early September, respectively. By that time, if the cobalt is the dominant source of the hard X-ray emission, we should observe a drastic cutoff in the light curve, independently of the details of the envelope structure.

III. SOFT X-RAY EMISSION

The emission of low-energy X-rays is the single most unexpected, most important, and still unexplained feature of SN 1987A. The flux measured by Ginga cannot be accounted for otherwise, unless an unknown source with very unusual properties is in the field of SN 1987A (Y. Tanaka, private communication); also, the *Ginga* detection is compatible with the present *Mir-Kvant* TTM upper limit (R. Sunyaev, private communication).

The observations show a spectrum with a slope similar to the hard X-rays, but misaligned with respect to them, in the sense of lying below their extrapolation. The average luminosity has remained basically constant since the onset, but there have been variations with time scales of days to weeks (especially in the lower *Ginga* band, 6–16 keV). Most variations appeared as drops from a predominant steady level; some of them might have been observed at higher energies with a smaller amplitude (Makino 1988*a*). The largest change, however, was an increase observed in 1988 January, when the soft X-rays went close to be aligned with the hard X-rays (Makino 1988*b*). During the flare an emission line of ionized iron was observed, whereas at any other time only upper limits are available (Tanaka 1988).

There is a general consensus that low-energy X-rays cannot be explained as down-Comptonized γ-rays. The theory predicts a firm lower limit at about 20 keV, which depends on the metallicity of the LMC material only as the power 0.25 (McCray, Shull, and Sutherland 1987). Furthermore, the rapid variations would be difficult to explain in a model where the entire envelope were involved.

It has been suggested that the low-energy emission might be due to the envelope interacting with circumstellar material (Masai *et al.* 1987, 1988). In the baseline scenario the main emitter is the envelope itself, heated to X-ray temperatures by the reverse shock; the unevenness of the obstacles would produce the observed variations.

We have independent information on the distribution of matter around the presupernova. The weak burst of radio emission (Turtle *et al.* 1987) and the lack of simultaneous X-ray emission in the first few days after the explosion have been successfully accounted for in the minishell framework (Chevalier 1987); one deduces a relatively low density for the circumstellar material, in agreement with the properties of the wind expected from the blue supergiant progenitor: $n = 3.7 \times 10^{10}(3 \times 10^{12}\ \mathrm{cm}/r)^2$ cm^{-3}. When the density is extrapolated to the present location of the shock (approximately 3×10^{16} cm), one finds $n = 3.7 \times 10^2$ cm^{-3} instead of $n \geq 10^4$ cm^{-3}, as required by the present X-ray emission.

Alternatively, if one assumes that the required density is indeed there, a typical blue supergiant wind velocity (~ 550 km s^{-1}) would imply a mass-loss rate in excess of 10^{-4} $M_\odot$ yr^{-1}, which is extreme for a red supergiant already.

A variant of the model, where the obstacles are so dense that the direct shocks propagating through them are the main source of X-rays, can also be proven to be untenable (Fabian and Rees 1988).

Finally, the 1988 January flare is attributed to the envelope impinging on the interface between blue and red supergiant winds; but both theoretical arguments and UV line observations (Chevalier 1987; Panagia *et al.* 1987) point to this interface being located at about 10^{18} cm, rather than the required 3×10^{16} cm.

We are thus forced to identify the source of soft X-rays with the remnant neutron star and its immediate surroundings; by the same token, we are forced to conclude that only a few months after explosion there existed through the envelope lines of sight transparent to low-energy X-rays.

Two basic models have been proposed for the central source. Fabian and Rees (1988) suggest that the neutron star is accreting matter from a companion via a disk, and is functioning as a normal binary X-ray source; instead, Bandiera, Pacini, and Salvati (1988) suggest that the neutron star is functioning as a normal isolated pulsar and is feeding an X-ray bright plerion.

An accreting neutron star would account naturally for the luminosity of the soft X-ray component, which is comparable with the Eddington luminosity for one solar mass. It would also accommodate easily the variability, and the presence of ionized iron. On the other hand, a close companion would imply orbital velocities of at least 100 km s^{-1}, and mass motions of this magnitude should exist in the red and blue supergiant winds around the system; the UV lines thought to arise from such a wind, instead, are narrower than 20 km s^{-1} (Panagia *et al.* 1987).

The main advantage of the plerion hypothesis is that it naturally provides an internal pressure, which might be instrumental in piercing clean holes wherever the envelope is underdense. The variations (with the possible exception of the 1988 January flare) are explained as occultation episodes due to non-radial motions of the envelope fragments.

IV. A PLERION MODEL

The theory of plerions has been developed originally by Pacini and Salvati (1973); in a subsequent series of papers (Bandiera, Pacini, and Salvati 1984; Reynolds and Chevalier 1984), it has been adapted to a variety of cases. The basic postulate is that the remnant emission is due to synchrotron radiation, and that a central pulsar is the origin of both the relativistic electrons and the magnetic field.

Possible modifications to the original theory include a nonlinear expansion of the plerion, a spatial structure for the magnetic field, and a nonuniform particle distribution. Here, however, we will restrict ourselves to the following simplifying prescriptions:

1. The pulsar has the same physical parameters (mass, radius, magnetic field) as the Crab pulsar, apart from the period P_0, which is kept as a parameter; the spin-down has been neglected, since we model a very young plerion, and the pulsar energy output (L_0) is constant with time.

2. One-half of the rotational energy is transformed into large-scale magnetic field, which is homogeneously distributed throughout the plerion volume.

3. The remaining half of the input power goes into particle acceleration; the injected particles are distributed in energy according to a power law, whose index γ is a second free parameter. The maximum energy at injection is scaled from the one deduced for the Crab pulsar, according to the law $E_{\rm max} \propto P_0^{-2}$ (Bandiera, Pacini, and Salvati 1984).

4. As long as we deal with high-frequency emission, we neglect adiabatic losses in comparison with synchrotron losses; the only exception is the computation of the low frequency fluxes of Table 1.

In modelling the plerion expansion, we consider two possibilities:

Model (1): linear increase of the plerion radius

$$R = V_{\rm exp}\, t\,, \tag{7}$$

with velocity $V_{\rm exp} = 5000$ km s^{-1}; and

Model (2): interaction with homogeneous ejecta in homologous expansion (Reynolds and Chevalier 1984)

$$R = \left(\frac{50}{77}\,\frac{V_{\rm exp}{}^3 L_0}{M_{\rm ej}}\right)^{1/5} t^{6/5}\,, \tag{8}$$

with total mass of the ejecta $M_{\rm ej} = 10$ $M_\odot$ and maximum ejecta velocity $V_{\rm exp} = 5000$ km s^{-1}. Models (1) and (2) will be referred to as "kinematical" and "dynamical," respectively.

In the general case of an expansion law $R \propto t^\alpha$ ($\alpha = 1$ and $\alpha = 6/5$ correspond to the models above), as long as $1 < \gamma < 2$ an analytical expression can be given for the high-frequency emission of the plerion:

$$S_\nu = \left[\frac{2-\gamma}{\gamma-1}\left(\frac{\alpha+1}{3}\right)^{(2-\gamma)/4} \frac{L_{\rm Cr}{}^{(2+\gamma)/4} P_{\rm Cr}{}^{(3\gamma-2)}}{4c_2{}^{(2-\gamma)/2} E_{\rm Cr}{}^{(2-\gamma)}}\right] \times P_0{}^{-(3\gamma-2)} R^{3(2-\gamma)/4} t^{-(2-\gamma)/4} \nu^{-\gamma/2}\ {\rm ergs\ s^{-1}\ Hz^{-1}}\,. \tag{9}$$

Here ν is the photon frequency; $P_{\rm Cr}$, $L_{\rm Cr}$, and $E_{\rm Cr}$ are the period, total power, and maximum particle energy of the Crab pulsar at birth ($=17$ ms, 6.7×10^{39} ergs s^{-1}, 140 ergs, respectively; see Bandiera, Pacini, and Salvati 1984), while the coefficients c_1 and c_2 are related to the synchrotron total power and the effective photon frequency emitted by an electron ($-dE/dt = c_1 B^2 E^2$ and $\nu = c_2 B E^2$).

When choosing the normalization of the plerion contribution, we assume it to lie at the high points of the low-energy light curve (excluding the 1988 January peak, because of its uncertain origin); the low points of the light curve would correspond to partial occultations, and the plerion contribution to the hard X-rays would at present be a fraction $\sim 1/10$.

Table 1 gives the pulsar and plerion parameters for the kinematical and dynamical models, with $\gamma = 1.5$ and $t = 190^{\rm d}$. Note in particular $R_{\rm max}$, the maximum distance which can be traveled by electrons radiating at 6 keV: if the injection occurs at the pulsar, $R_{\rm max}$ is an upper limit to the size of the synchrotron nebula. From the shape of the observed light curve it can be argued that the nebula and the obscuring filaments have comparable sizes; if $\Delta t = 10^6$ s is a typical variability time scale, the filaments nonradial velocities are $\lesssim v = R_{\rm max}/\Delta t$, which is also given in Table 1.

The predicted nonthermal continuum fluxes in the optical

TABLE 1

PULSAR AND PLERION PARAMETERS DEDUCED FROM THE X-RAY EMISSION OF SN 1987A AROUND DAY 190

Parameter	Kinematical	Dynamical
P_0 (ms)	55	36
L_0 (ergs s^{-1})	5.9×10^{37}	3.2×10^{38}
R (cm)	8.0×10^{15}	4.6×10^{14}
B_{neb} (G)	0.05	8.3
R_{max} (cm)	2.7×10^{15}	1.3×10^{12}
v (km s^{-1})	27,000	13
m_V	17.8	17.2
F(10 μm) (ergs s^{-1} cm^{-2} μm^{-1})	3.0×10^{-14}	1.2×10^{-13}
F(1.3 mm) (mJy)	4.0	160

NOTE.—$\gamma = 1.5$; $t = 190^d$. See text for the assumptions underlying the two models.

and the IR do not conflict with the existing observational limits; in the radio, the model fluxes are comparable with the recent detection at 1.3 mm (Chini *et al.* 1988). We must stress, however, that our computations refer to a time earlier than the actual observations, and that the radio luminosity can be affected by opacity effects even on lines of sight which are fully transparent to the X-rays. A thermal origin for the radio emission is a plausible alternative (Salvati *et al.* 1989).

We note also that an energetic pulsar should manifest itself as an additional energy source for the bolometric thermal emission. A pulsar input in the range 6×10^{37}–3×10^{38} ergs s^{-1} (as required by the soft X-ray flux) should soon become appreciable in the optical light curve, and indeed preliminary evidence for it has already been reported (e.g., Burki and Cramer 1989).

V. CONCLUSIONS

The high-energy emission from SN 1987A is providing important information about explosive nucleosynthesis, hydrodynamics of the supernova, and the early life of neutron stars. The picture which emerges seems to confirm a number of theoretical predictions, but also points towards a rather complex hydrodynamical scenario. In particular, observations show that a simple homogeneous picture for the explosion is far from real. The distribution of matter in the envelope is instead characterized by large-scale inhomogeneities and by the early formation of distinct clumps and filaments.

The X-ray emission from SN 1987A probably results from at least two different processes. On the one hand, the optical light curve points toward the formation of about 0.07 $M_\odot$ of ^{56}Co, and this is confirmed by the detection of the corresponding γ-ray lines. Their persistence at a nearly constant level for many radioactive decay time scales shows that the distribution of ^{56}Co inside the stellar material is inhomogeneous, and arranged in such a way as to give little luminosity evolution (until now). Some long-lasting flux of hard X-rays is the natural consequence of the down-Comptonization of part of the γ-rays; but, if this were the only important source, the hard X-rays could not last beyond the end of 1988, since then an amount of ^{56}Co larger than 0.07 $M_\odot$ would be required. Below 20 keV the flux cannot be due to radioactivity, because of photoelectric absorption in the envelope. The most natural interpretation is that it is due to a pulsar nebula seen through a fragmented envelope. This would explain the long-term stability and short-term fluctuations of the low-energy X-ray emission. The contribution of the pulsar nebula to the flux above 20 keV is not negligible *a priori*, but its actual level cannot be established with confidence. This will become clear in the coming months, with the gradual disappearance of the photons which originate from the radioactive material.

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