THE PROGENITOR OF THE NEW COMPTEL/ROSAT SUPERNova REMNANT IN VELA

WAN CHEN and NEIL GEHRELS
NASA/Goddard Space Flight Center, Code 661, Greenbelt, MD 20771; chen@milkyway.gsfc.nasa.gov

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ABSTRACT
We show that (1) the newly discovered supernova remnant (SNR) GRO J0852−4642/RX J0852.0−4622 was created by a core-collapse supernova of a massive star and (2) the same supernova event that produced the 44Ti detected by COMPTEL from this source is probably also responsible for a large fraction of the observed 26Al emission in the Vela region detected by the same instrument. The first conclusion is based on the fact that the remnant is currently expanding too slowly given its young age for it to be caused by a Type Ia supernova. If the current SNR shell expansion speed is greater than 3000 km s$^{-1}$, a 15 $M_\odot$ Type II supernova with a moderate kinetic energy exploding at about 150 pc away is favored. If the SNR expansion speed is lower than 2000 km s$^{-1}$, as derived naively from the X-ray data, a much more energetic supernova is required to have occurred at ~250 pc away in a dense environment at the edge of the Gum Nebula. This progenitor has a preferred ejecta mass of $\leq 10 M_\odot$, and therefore it is probably a Type Ib or Type Ic supernova. However, the required high ambient density of $n_b \geq 100$ cm$^{-3}$ in this scenario is difficult to reconcile with the regional CO data. A combination of our estimates of the age/energetics of the new SNR and the almost perfect positional coincidence of the new SNR with the centroid of the COMPTEL 26Al emission feature of the Vela region strongly favors a causal connection. If confirmed, this will be the first case in which both 44Ti and 26Al are detected from the same young SNR, and together they can be used to select preferred theoretical core-collapse supernova models.

Subject headings: gamma rays: observations — supernova remnants — supernovae: general

1. INTRODUCTION

Recently, the COMPTEL instrument aboard the Compton Gamma Ray Observatory discovered a new supernova remnant (SNR), GRO J0852−4642, as a strong source of 44Ti 1.16 MeV line emission (Iyudin et al. 1998). The new source is located in the constellation Vela in the direction of $l \sim 266^\circ$ and $b \sim -1^\circ$. Due to the short lifetime of 44Ti, $\tau = 90.4 \pm 1.3$ yr (Norman et al. 1997), the fact that COMPTEL can detect this source at all indicates that it is a young SNR at a distance less than 500 pc with an age probably less than 10$^\tau$ 900 yr.

The COMPTEL 44Ti source was soon identified with a previously unknown shell-type SNR in ROSAT data of the Vela region collected during its 1990 all-sky survey (Aschenbach 1998). Designated as RX J0852.0−4622, the new SNR is seen within the error circle of the COMPTEL source, but only at energies greater than 1.3 keV. The shell has a radius $\theta \sim 1^\circ$. Spectral analysis reveals that X-rays from the majority of the shell are of thermal origin with a temperature of $kT = 2.5_{-0.6}^{+0.3}$ keV, which is significantly greater than that of the surrounding area. This is why the shell can be identified only at high energies, and this also indicates a young age. The northern limb of the shell appears brighter and has an even higher temperature of $4.7_{-3.5}^{+1.5}$ keV. This component can also be fitted by a power law with photon index $\alpha = -2.6_{-2.3}^{+2.3}$. In addition, the ROSAT data gives an upper limit of $n_b < 0.4(d/500$ pc)$^{-1/2}$ cm$^{-3}$ to the density of the ambient medium in which the progenitor of RX J0852.0−4622 exploded (Aschenbach 1998).

We show in this Letter that, assuming that COMPTEL and ROSAT detected the same source, the above observed properties can place rather stringent constraints on the nature of the progenitor star of GRO J0852−4642/RX J0852.0−4622 (hereafter GRO/RX J0852).

The supernova that produced the observed radioactive 44Ti would also have synthesized about the same amount of radioactive 26Al, which has a much longer lifetime of $1.05 \times 10^8$ yr and whose decay produces a $\gamma$-ray photon at 1.8 MeV. Indeed, the COMPTEL instrument has detected significant 1.8 MeV emission from the Vela region, whose origin has previously been attributed to the Vela SNR (Diehl et al. 1995) but later became less certain (Diehl et al. 1999). However, the better coincidence of the centroid of the COMPTEL 1.8 MeV feature with the location of GRO/RX J0852 prompts us to investigate if it is GRO/RX J0852 that is responsible for most of the observed 26Al emission.

2. THE NATURE OF THE PROGENITOR

The observed 44Ti line flux is $F = (3.8 \pm 0.7) \times 10^{-5}$ cm$^{-2}$ s$^{-1}$ (5.6 $\sigma$). For a nominal 44Ti yield of $Y = 5 \times 10^{-5}$ $M_\odot$ per supernova explosion (SNE; Woosley & Weaver 1994, 1995, hereafter WW94, WW95; Thielemann, Nomoto, & Hashimoto 1996), the observed 1.16 MeV flux restricts the age of the source to be

$$t \leq \tau \ln \left( \frac{Y}{4\pi d^2 \tau m_{4u} F} \right) = 840 \pm 20 \text{ yr} \quad (1)$$

at a distance of 100 pc. In theoretical models, the yield ranges from a low of $5 \times 10^{-5}$ $M_\odot$ to a high of $4 \times 10^{-3}$ $M_\odot$. We calculate the constraint on the age versus distance for the range of the theoretical yields, as shown by the solid curves in Figure 1.

While the thermal nature of the bright northern rim is debatable, the thermal X-ray emission from most of the shell is undoubtedly generated from shocks as the supernova blast wave runs into the ambient medium. The observed shell temperature of 2.5 keV implies that the shock front is currently
and where is the mass of the ejecta in units of solar masses

gives another set of constraints on the relationship between age
of 2000±5000 km s⁻¹. From arguments we present below, is probably in the range
value could be greater by as much as a factor of 2±3 (Scudder
The validity of such a direct conversion from the electron tem-
perature to the shock front speed requires the electrons to be
in equilibrium with ions in the postshock region. For colli-
sionless shocks (as is the case for most young SNRs), this
condition may not always hold, if, for example, the magnetic
coupling between the ions and electrons is not effective enough.
In such cases, the ion temperature, which reflects the true shock
speed, could be greater than the electron temperature. There-
fore, \( v_e \) calculated above is probably a lower limit; the real
value could be greater by as much as a factor of 2–3 (Scudder
1995).

Over the lifetime of the SNR, the mean expansion velocity
\( \langle v_e \rangle \) may be higher than \( v_e \), depending on its progenitor type.
From arguments we present below, \( \langle v_e \rangle \) is probably in the range
of 2000–5000 km s⁻¹. For given \( \langle v_e \rangle \), the observed shell radius
gives another set of constraints on the relationship between age
and distance, as shown by the dashed lines in Figure 1. We see that
the most probable value for the distance to the new
SNR is in the range between 100 and 300 pc and for the age
is between 600 and 1100 yr. At a distance of 250 pc, the SNR
has a radius of about 4.4 pc.

Now we discuss what possible progenitors are allowed by
the observed and derived properties of the SNR. We first as-
sume that the environment in which the progenitor exploded
has a uniform density \( n_H = 0.05 \) cm⁻³, consistent with the limit
derived from the ROSAT data. For an SNe in such a medium,
there is a universal solution for the early stages of SNR evo-
lution (McKee & Truelove 1995). Immediately after the ex-
losion, the blast wave expands freely during the so-called
ejecta-dominated phase. The ejecta maintains a constant
expansion velocity with a maximum value of

\[
v_e = \left( \frac{16 E}{3 M_e \, n_H} \right)^{1/2} = 1300^{+1020}_{-140} \left( \frac{kT}{2.5^{+4.5}_{-0.7} \text{keV}} \right)^{1/2} \text{km s}^{-1}, \tag{2}
\]

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\[
v_e = \left( \frac{10 E}{3M_e} \right)^{1/2} = 1.3 \times 10^4 E_{51}^{1/2} M_e^{-1/2} \text{km s}^{-1}, \tag{3}
\]

where \( M_e \odot \) is the mass of the ejecta in units of solar masses and
\( E_{51} \) is the kinetic energy of the SNe in units of \( 10^{51} \) ergs.
For a Type Ia supernova (SNIa) of \( M_e \odot \sim 1.4 \), \( v_e \) is more than
10,000 km s⁻¹. For a Type II supernova (SNII) of \( M_e \odot \geq 10 \), \( v_e \) can be much smaller. Therefore, if the progenitor of the
new SNR is an SNIa, the expansion must have been significa-
cantly slowed down, which requires an old age. If the progen-
itor star is more massive than 30 \( M_\odot \), the free-expansion
velocity of an SNII is close to the observed shock front velocity
\( v_e \).

After the blast wave sweeps up about the same amount of
mass as the ejecta, the SNR evolution enters the Sedov-Taylor
phase, during which time the SNR shell velocity decreases with
time as \( v \propto t^{-2/3} \). The timescale for the onset of the Sedov-
Taylor phase is (McKee & Truelove 1995)

\[
t_{ST} \sim 570 E_{51}^{-1/2} M_e^{-5/6} M_\odot^{-1/3} n_H^{-1/3} \text{yr}, \tag{4}
\]

where \( n_{H,0.05} = n_H/(0.05 \text{ cm}^{-3}) \). Therefore, an SNII spends
much more time in the free-expansion phase than an SNIa does.
Also, a higher ambient density of \( n_H \sim 1 \text{ cm}^{-3} \) would reduce
\( t_{ST} \) by a factor of 2.7.

It immediately follows from equation (3) that if the progen-
itor of GRO/RX J0852 was an SNIa, the SNR would have to be
in the Sedov-Taylor phase by now because of the observed
small shock velocity. However, for a typical SNIa explosion
with \( \sim 1 \times 10^{51} \) ergs of kinetic energy, it would take about

\[
t_{es} \sim t_{ST} \left( \frac{v}{v_e} \right)^{-5/2} = 1.5 \times 10^5 E_{51}^{3/4} M_e^{-5/12} M_\odot^{-1/3} n_{H,0.05}^{-1/3} \text{yr} \tag{5}
\]

for the ejecta to slow down from an initial expansion velocity
of 11,000 km s⁻¹ to the observed 1300 km s⁻¹. This age can
drop to 10⁴ yr if the real \( v_e \) is a factor of 3 higher than that
derived from the observed electron temperature by equation
(2), but it is still more than an order of magnitude longer than
the data suggest. For an SNIa model to work, the only other
alternative is then to increase the ambient density by a factor of
at least 10,000 to \( \geq 500 \text{ cm}^{-3} \).

The above argument can be more clearly illustrated by con-
sidering the theoretical SNR expansion velocity as a function
of the SNR age shown in Figure 2. The constant velocity por-
tion of the curves represents the free-expansion (or ejecta-dom-
inated) phase, followed by the \( v \propto t^{-2/3} \) Sedov-Taylor phase.
We have adopted the kinetic energy for an SNIa to be around
\( 1 \times 10^{51} \) ergs and for an SNII to be in the range \( (1–2) \times 10^{51} \) ergs (WW94, WW95). The ejecta mass of an SNIa
ranges from the standard model of 1.4 \( M_\odot \) to special He-detonated
models of 0.8 \( M_\odot \) (WW94). The ejecta mass of an SNIII is
in the range between 8 and 40 \( M_\odot \). The shaded area in Figure 2
represents the parameter space that is preferred by the obser-
Vations. We have allowed a factor of 3 uncertainty in the current
shell expansion speed.

If we take the default ambient gas density as 0.05 cm⁻³, we
see from Figure 2 that the SNIa evolution track is totally in-
consistent with the observations. To match the current expan-
sion speed, the ambient density has to be higher than 500 cm⁻³
for the SNIa model to be marginally acceptable. In this case,
we chose an He-detonation model from WW94 with an ejecta
mass of 1.1 \( M_\odot \), which has a \(^{56}\)Ni yield of \( \sim 2 \times 10^{-1} \) \( M_\odot \). The mean expansion velocity for this case is about 5100 km s⁻¹ at
an age of 800 yr. From Figure 1, we see that this model with
very high density does have a solution with a distance
\( \sim 240 \) pc.

For the low ambient density condition, on the other hand, we
see from Figure 2 that (1) there is a range of SNII models

![Figure 1: Constraint on the SNR distance and age by average shock velocity and \(^{56}\)Ti yield from a single SNe.](image-url)
allowed and (2) all of these models are still in the free-expansion phase, so \( \dot{v} = v_t \). The model with the highest allowable free-expansion speed of \( \sim 3700 \text{ km s}^{-1} \) (upper dotted line, Fig. 2) has \( E_{\text{SN Ia}} = 1.2 \) and \( M_{\text{SN Ia}} = 15 \); it produces \( 5.7 \times 10^{-3} M_{\odot} \) of \( ^{44}\text{Ti} \) (WW95). Figure 1 then tells us that the source must be at a distance of about 150 pc and an age of about 700 yr. Other models with smaller expansion speed have much greater progenitor mass of 25–40 \( M_{\odot} \). The lower line of the SNII range in Figure 2 corresponds to \( E_{\text{SN II}} = 1.2 \) and \( M_{\text{SN II}} = 40 \). However, this model produces only \( 2.7 \times 10^{-11} M_{\odot} \) of \( ^{44}\text{Ti} \) (WW95); in fact, the \( ^{44}\text{Ti} \) yield of all the models in WW95 that have \( v_t \leq 3000 \text{ km s}^{-1} \) is less than \( 10^{-9} M_{\odot} \).

Therefore, if the current SNR expansion speed is less than 2500 km s\(^{-1}\), the remnant of a viable core-collapse supernova model has also to be in the Sedov-Taylor phase, which requires a large ambient density of \( n_{\text{HI}} \geq 100 \text{ cm}^{-3} \). For reasons we discuss below, this condition dictates the source distance to be at least 250 pc. From Figure 1, we see that at such a distance the SNR mean expansion speed has to be \( \geq 5000 \text{ km s}^{-1} \) because the \( ^{44}\text{Ti} \) yield of these models is less than \( 3 \times 10^{-4} M_{\odot} \) (WW95). Therefore, we need small ejecta mass and large kinetic energy. The lowest ejecta mass (9.7 \( M_{\odot} \)) model of WW95 has a \( ^{44}\text{Ti} \) yield of \( 6 \times 10^{-3} M_{\odot} \) and also a relatively low kinetic energy, \( 1.3 \times 10^{51} \) ergs. It will produce a mean expansion speed of only 3700 km s\(^{-1}\) for \( n_{\text{HI}} = 300 \text{ cm}^{-3} \). A more energetic explosion usually requires a much more massive progenitor and thus even lower mean expansion speed. It is possible, however, that a massive star may undergo a supernova explosion (resulting in a Type Ib or Type Ic supernova, for example) after it loses a significant fraction of its envelope because of strong stellar winds. While WW95’s calculations did not take this effect into account, we assume that it is conceivable that some core-collapse supernovae could have a kinetic energy as much as \( 2.5 \times 10^{51} \) ergs and at the same time an ejecta mass of 10 \( M_{\odot} \). If so, Figure 2 shows that such a model (marked as SNIIb) can produce a marginally acceptable evolution track in an ambient density of 100 cm\(^{-3}\). The mean expansion speed in this case is 5100 km s\(^{-1}\), consistent with the required distance of 250 pc (Fig. 1).

### 3. DISCUSSIONS

We have seen that whether the progenitor of GRO/RX J0852 is an SNII or an SNII, if the current SNR expansion speed \( v_R \) is less than 2500 km s\(^{-1}\), it is almost exclusively required that the SNE occurred in a high-density region: \( n_{\text{HI}} \geq 100 \text{ cm}^{-3} \) for a SNII and \( \geq 500 \text{ cm}^{-3} \) for an SNIIa. The distance to the source in either case is about 250 pc, and most of the space along the line of sight still has a very low density of \(<1 \text{ cm}^{-3} \). We now discuss whether the required high-density medium exists at the required direction and distance.

Along the general direction of GRO/RX J0852, the only possible candidate for a high-density region within 500 pc is the Gum Nebula. While most of the Gum Nebula is filled with ionized, low-density gas (Sahu & Sahu 1993; Reynolds 1976), recent reanalysis of the historical H\( \alpha \) 21 cm data revealed two distinct structures associated with the Gum Nebula (Reynoso & Dubner 1997). One is a large, 1.4 \( \times 10^5 M_{\odot} \), disk of neutral gas that is 150 pc in radius and \( \sim 50 \text{ pc} \) in thickness. The other is a smaller, thick H\( \alpha \) shell of 2.1 \( \times 10^4 M_{\odot} \) with a radius of \( \sim 60 \text{ pc} \) (Dubner et al. 1992), roughly at the center of the disk. Both the disk and the shell share a distance of 500 \( \pm 100 \text{ pc} \). Therefore, the minimum distance to the edge of the disk is about 250 pc. The mean number density of the disk and the shell is 1.6 and 0.95 cm\(^{-3}\), respectively, far below the required value for the model progenitor of GRO/RX J0852. Thus, both the SNIIa and SNIIb models require the presence of additional, much denser gas components at the edge of the H\( \alpha \) disk. Because the Gum Nebula was probably created by some ancient supernova events, it is conceivable that the highest density regions are located near the edge of the structure.

A recent CO survey has shown complex molecular cloud structure in the Vela region (Murphy & May 1991). The map shows that GRO/RX J0852 falls on the edge of one of the CO hot spots, but there is no morphological evidence that the cloud is disturbed by the SNR. The distances to the components of this so-called Vela molecular ridge are estimated to be 1–2 kpc based on the radial velocity profile, further suggesting that they may be unrelated to the SNR. If for any reason these distance estimates were inaccurate and the CO hot spot near GRO/RX J0852 had a distance of 250 pc instead of 1–2 kpc, the maximum mean number density of this component would be even smaller than the observed 16 cm\(^{-3}\) (Murphy & May 1991) and fall short of the required minimum density of 100 cm\(^{-3}\). Therefore, an extreme density of 500 cm\(^{-3}\), along with the SNIIa origin of the new SNR, can be ruled out by the H\( \alpha \) and CO data; even the SNIIb progenitor also becomes a difficult proposition.

If GRO/RX J0852 was created by an SNII event about 800 yr ago, an unavoidable consequence is that the same explosion that produced the observed \( ^{44}\text{Ti} \) will also synthesize a certain amount of \( ^{26}\text{Al} \). Specifically, for the SNIIb event favored by a small \( v_R \), the \( ^{26}\text{Al} \) yield is \( 3.6 \times 10^{-4} M_{\odot} \) with a 1.8 MeV line flux of \( \sim 6.7 \times 10^{-3} \) photons s\(^{-1}\) cm\(^{-2}\) at a distance of 250 pc. This flux is about a factor of 3 greater than the observed flux observed from the Vela region by COMPTEL (Diehl et al. 1995). The 15 \( M_{\odot} \) SNII model favored by the condition \( v_R > 3500 \text{ km s}^{-1} \), on the other hand, has an \( ^{26}\text{Al} \) yield of \( 4.3 \times 10^{-5} M_{\odot} \), which would produce a 1.8 MeV line flux of \( 2.2 \times 10^{-3} \) photons s\(^{-1}\) cm\(^{-2}\), comparable to the observed value. It is thus intriguing to postulate that GRO/RX J0852 is
also a major contributor to the Vela $^{26}$Al feature. Indeed, recent reexamination of the Vela data has argued against previous attribution of the Vela $^{26}$Al flux to the Vela SNR (e.g., Diehl et al. 1999). The centroid of the Vela $^{26}$Al feature, at $l = 267^\circ$ and $b = -1^\circ$, is $\sim 4^\circ$ away from the center of the Vela SNR, but falls right on top of GRO/RX J0852. The combination of the positional coincidence and the good agreement between the expected 1.8 MeV flux and the observed value strongly favors this interpretation. Since the 1.8 MeV Vela feature is probably slightly extended, it seems that both the Vela SNR, or a local concentration of the massive-star formation tracers (Diehl et al. 1999), and GRO/RX J0852 have contributed, while the majority of the flux comes from the latter.

4. CONCLUSIONS

We have investigated the parameter space allowed by the observed properties of the newly discovered SNR GRO/RX J0852, assuming that the COMPTEL $^{44}$Ti source and the ROSAT SNR are the same source. We conclude that the likely progenitor of this new SNR is a massive star, and its precise type depends on the correct determination of the current SNR shell expansion speed $v_s$. It is most probable that the true value of $v_s$ is more than a factor of 2 greater than that derived from the shell electron temperature using X-ray data and the progenitor is a $15 M_\odot$ SNII with a moderate SNe kinetic energy. The age of the source is $\sim 700$ yr, and the distance is $\sim 150$ pc. If the current $v_s$ were small, on the other hand, a much more energetic SNIIb or SNIIc event would be required to have exploded 800–900 yr ago in a high-density medium about 250 pc away. This latter interpretation, however, has the difficulty of finding observationally the required high-density gas at the required distance. The recently discovered cold neutral gas structure associated with the nearby Gum Nebula seems not to be able to provide the required high density.

It is likely that the nearest SNE less than 1000 yr ago in the Vela region produced both the $^{44}$Ti and $^{26}$Al emission features detected by COMPTEL. This offers an exciting new avenue to test the core-collapse SNe models since the explosive yields of $^{44}$Ti and $^{26}$Al are related. Because of its much shorter lifetime, $^{44}$Ti is usually better suited for discovering young SNRs. However, since it just so happened that the age of GRO/RX J0852 is about 8–10 times the lifetime of $^{44}$Ti, its $^{44}$Ti flux has dropped by a factor of 3000–10,000 from its peak value and now almost equals that of $^{26}$Al, which has a decay lifetime that is $\sim 10,000$ times longer. It is thus worth noting that for SNRs older than about 1200 yr, $^{26}$Al is a better radionuclide to use for SNR searches.

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