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Massive Supernovae, Orion Gamma Rays, and the Formation of the Solar System

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ABSTRACT

We discuss the source of the enhanced carbon and oxygen low-energy cosmic-ray flux in the Orion star-forming region and attribute it to the acceleration of the surface layers of a massive supernova, probably of Type Ib. The gamma rays from Orion are produced by that fast CO ejecta. In this model there would be few Orion-like gamma-ray sources in the Galaxy at any one time. We also postulate that a massive supernova produced the short-lived extinct radioactivities injected into the molecular cloud core that produced the solar system. We find that relative to ^{26}Al the other short-lived extinct radioactivities are excessively produced in massive supernovae but are likely to be more attenuated by postexplosion fallback than ^{26}Al. This is a revival of the supernova trigger hypothesis; to obtain the correct dilutions of the extinct radioactivities, the distance from the supernova to the impacted molecular cloud core must be a few parsecs, and the effective projected collecting area of the cloud must be significantly less than normal core radii.

Subject headings: gamma rays: theory—solar system: formation—supernovae: general

§1. INTRODUCTION

The discovery of 4.4 and 6.1 MeV gamma rays, from the deexcitation of ^{12}C and ^{16}O, in the direction of the Orion Nebula (Bloemen et al. 1994) generated a flurry of theoretical activity. Clayton (1994) suggested that if the energetic carbon and oxygen was part of an accelerated solar abundance spectrum of low-energy cosmic rays, then the bombardment of the gas in star-forming regions by such a spectrum might account for the copious ^{26}Al in the interstellar medium and also the production of extinct radioactivities in the molecular cloud that collapsed to form the solar system. These suggestions soon encountered problems, for the Compton Imaging Telescope (COMPTEL) had failed to observe the 1–3 MeV gamma rays from intermediate elements that would be produced in this scheme (Ramaty, Kozlovsky, & Lingenfelter 1995b), and Ramaty, Kozlovsky, & Lingenfelter (1995a) found that any reasonable bombardment scheme, with a solar abundance spectrum for either the bombarding particles or the target, produced a ^{9}Be/^{26}Al ratio greater than that in the primitive solar nebula. Adequate ^{26}Al production without overproduction of ^{9}Be requires that particle energies must be less than 10 MeV nucleon^{-1} (Clayton & Jin 1995). Hence any power-law particle energy spectrum would have to be cut off steeply at this energy. Thus we have been prompted to take a fresh look at both aspects of the situation.

§2. ORION GAMMA RAYS

Orion is the closest large star-forming molecular cloud complex. It contains a very active site of massive star formation, the Orion OB1 association, with subclusters of stars having ages of less than 1, 1.7 ± 1.1, 4.6 ± 2, and 11.4 ± 1.9 Myr for subclusters 1d, 1b, 1c, and 1a, respectively (Brown, de Geus, & de Zeeuw 1994). The age of subcluster 1b is particularly uncertain, older estimates having been 5.1 and 7 Myr. Thus currently subcluster 1d would not produce supernovae, 1b may produce very massive (60–120 $M_\odot$) supernovae if its age is near the top of the range of uncertainty, 1c may produce supernovae in the range 25–120 $M_\odot$ within its range of age uncertainty, and 1a may produce supernovae in the range 14–17 $M_\odot$ (Schaller, Schaerer, & Maeder 1992). A large interstellar superbubble has formed that extends from Orion OB1 more than 300 pc toward the Sun but with smaller dimensions in the transverse directions (Burrows et al. 1993). The superbubble emits soft X-rays from a low-density hot plasma. Such superbubbles are frequently produced from OB associations when several massive supernovae have exploded. In Orion the supernovae responsible for producing the superbubble would be those in subcluster 1a.

To interpret the Orion gamma rays we require a supernova with a mass above 40 $M_\odot$, and we note that one or two of the Orion subclusters can produce one. The presupernova evolution of such a massive star, including the effects of mass loss, has been studied by Woosley, Langer, & Weaver (1993, henceforth WLW). In this entire mass range, the time required to evolve (with mass loss) to the supernova explosion ranges from slightly more than 3 to about 5 Myr. Most of this time is spent in main-sequence hydrogen burning with relatively small mass loss, followed by a few hundred thousand years for the remainder of the presupernova evolution. As helium burning switches to carbon burning in the stellar core, the star becomes a Wolf-Rayet (W-R) object that ejects most of its mass at velocities of 2–3 × 10^{8} cm s^{-1}. The mass is quickly reduced and the mass-loss rate becomes very small during the roughly 10^{4} yr of the carbon burning and the small additional time to reach central core collapse (Schaller et al. 1992); the lower mass-loss rate results from a reduction in stellar radius (Abbott & Conti 1987). At supernova time the remaining mass ranges from 11 to as small as 4 $M_\odot$ (at about 60 $M_\odot$ initial main-sequence mass). The upper layers of the star then contain principally a mixture of helium, carbon, and oxygen (Woosley, Langer, & Weaver 1995).

WLW plot the terminal velocity of the material ejected from a 60 $M_\odot$ supernova as a function of the presupernova mass. The outermost layer is ejected at more than $\sim$2 × 10^{9} cm s^{-1}. Typically, the total kinetic energy is about 1–2 × 10^{51} ergs. For the density gradients in the outer layers of W-R stars, expansion velocities of 2–5 × 10^{9} cm s^{-1} are obtained in a mass of about 10^{-3} $M_\odot$.

The nature of Type Ib and Ic supernovae, and whether they result from two distinctly different evolutionary paths, is still under debate (see, e.g., Wheeler et al. 1995). Type Ib+c supernovae may result from the binary evolution of low-mass stars or from the final stages in the evolution of massive stars. In either case the final stage is a CO “core” of about 2–4 $M_\odot$. The resulting spectra should be almost indistinguishable. Both types of progenitor may well be realized in nature. Our model requires that an exploding massive star should have comparable amounts of C and O, with quite a lot of helium, in the top layer. It would be classified as a Type Ib supernova unless the helium content is very low, in which case it would probably be classified as a Type Ic.

These outer carbon-oxygen layers are ejected at an energy of 1.5–15 MeV nucleon^{-1}, and most of this range of energies is sufficient to excite the 4.4 and 6.1 MeV gamma rays if the ions strike hydrogen or helium within the Orion Nebula; such an event would account nicely for the Orion gamma rays. Yields near 10^{-3} γ of 4.4 and 6.1 MeV per stopped C or O nucleus are achievable (Clayton & Jin 1995).

The expanding material in the W-R wind will probably not form a spherical shell. In 10^{4} yr the wind material, if expanding into a void, would travel about 30 pc. In the Orion OB1 association, the wind directed toward the inner part of the molecular cloud would be slowed down by running into the molecular gas well short of this distance; that directed outward into the interstellar superbubble could travel this distance unimpeded. The supernova ejecta would travel about an order of magnitude faster than the W-R wind and thus would overtake the main body of it in the order of 10^3 yr in the superbubble, and sooner in the direction of the interior of the cloud. The collision of the ejecta with the wind material would generate the Orion gamma rays with the efficiency noted above. If the ejecta should escape through any holes that might develop in the wind material, it would collide with surrounding hydrogen and also generate these gamma rays. Gamma-ray emission should start at a low level as the ejecta encounter small amounts of wind material ejected most recently from the star and increase as the collisions occur with the main bulk of the wind material at larger distances. The slower ejecta from somewhat deeper in the supernova envelope would produce gamma rays over a longer time. The total amount of stellar material energetic enough to produce the gamma rays is about 10^{-3} $M_\odot$ or more (WLW). This material is sufficient to generate the gamma rays at the observed rate for a few thousand years, and this time is consistent with estimates based on distances traveled as given above.

Most implosion-type supernovae have remnants detectable for thousands of years, particularly in nonthermal radio emission, and so the event postulated in our model might be expected to be a prominent feature in the Orion OB1 association. However, we presume that easily detectable supernova remnants are fed energetic electrons from residual pulsars to provide the radio emission. Such supernova explosions are expected to have a significant amount of mass fallback inside some "mass cut" mass fraction, induced in part by partial reflection of the supernova shock at boundaries of chemical discontinuity, estimated to range from 0.1 to 0.4 $M_\odot$ for a 25 $M_\odot$ star (Höflich & Thielemann 1995), and probably more for higher masses. Since we believe the Orion gamma rays to have been produced by a very massive star of initially about 60 $M_\odot$, we believe it is plausible that the fallback in this case may have pushed any neutron star remnant over the threshold of gravitational collapse to form a black hole, thus making such nonthermal effects of this explosion very hard to detect in Orion. The thermal radio and infrared emission from shocked gases in the surrounding cloud may be significant but hard to distinguish from all the other nonthermal emission in the Orion region.

This model makes predictions inconsistent with the assumptions that have previously been made that the enhanced flux of low-energy cosmic rays in Orion is the normal state in a star-forming region, and thus that the Galaxy should be filled with "Orions." In our model the Orion gamma-ray emission is quite short lived, and hence although Orions are likely to be common in massive star-forming regions, very few perhaps most often zero, are likely to be visible at any one time.

§3. SHORT-LIVED EXTINCT RADIOACTIVITIES IN THE SOLAR SYSTEM

Studies of primitive meteoritic material formed in the early solar system have frequently found the decay products of several relatively short lived extinct radionuclides. An early attempt to assign these to stellar sources was made by Cameron (1993). The shortest lived of these are ^{41}Ca, ^{26}Al, ^{60}Fe, and ^{53}Mn. Their mean lives are given in Table 1.

The primary puzzles concerning these radionuclides have been to produce them with the right relative abundances in one or more stellar sources and to transport them from their place of manufacture to the primitive solar nebula before the radioactivity decays. A principal attraction of the Orion phenomenon was that the energetic particles postulated to produce the radioactive nuclides were already present within the region and that the place of production could be the fragment of the molecular cloud that might already be collapsing to form the primitive solar nebula. In an alternative model one must find one or more stellar nucleosynthesis sources close to the molecular cloud core that will form the solar nebula and must quickly transport the radionuclides to that core. This scenario becomes more plausible if the transport of the radioactivities can also trigger the collapse of that core.

We postulate a star-forming region having an OB association similar to that of Orion OB1, with massive stars becoming supernovae, but we neither need nor invoke the Orion gamma-ray phenomenon, and a different mass range of supernovae may be involved. All four of the radionuclides discussed above are made in massive supernova explosions and are ejected with the outflowing material from the supernova explosion. They are quickly transported over distances of a few parsecs, and we discuss what happens when the supernova shock encounters a molecular cloud core and compresses it. Such a supernova trigger was earlier discussed by Cameron & Truran (1977) and was also mentioned recently by Boss (1995), who considered the effects of an interstellar shock wave impinging on a cloud core; however, he chose to pursue a different variant of the idea.

We are indebted to Stan Woosley (WLW; Weaver & Woosley 1993; Woosley & Weaver 1995) for providing us with detailed data on his extensive series of supernova simulations. To represent a range of possibilities, we discuss the cases of 25 $M_\odot$ and 60 $M_\odot$ supernovae, situated in or in close proximity to the molecular cloud in which they were born and having solar abundances initially. The 25 $M_\odot$ supernova is typical of a range of masses in which the hydrogen envelope is not completely lost prior to the explosion, and thus there is no W-R phase. For the four extinct radionuclides of interest the relevant quantities are listed in Table 1. Row 1 gives the mean life, row 2 the reference nuclide (of the same element), and row 3 its abundance in the Sun. Row 4 gives the abundance ratio of the radionuclide to its reference nuclide as measured from the decay products in meteorites. Combining rows 3 and 4 gives in row 5 the radionuclide abundances in the Sun (in solar masses). Row 6 gives the yield of the radionuclides for a 25 $M_\odot$ supernova from the calculations of Woosley & Weaver (1995). From the ratio of rows 6 and 5 we get in row 7 the dilution factor needed to reduce the amount of a radionuclide produced by the supernova to the amount that ends in the Sun and solar system.

Table 1 shows that ^{41}Ca, ^{60}Fe, and ^{53}Mn are required to have dilution factors between 1 and 3 orders of magnitude greater than ^{26}Al. We see no plausible way to increase the supernova yield of ^{26}Al. Radioactive decay will decrease the abundance of ^{41}Ca by about 2 orders of magnitude during transport between the supernova and the completion of the triggered collapse to form the solar nebula, and the abundance of ^{26}Al will be decreased by about a factor of 2 during this transport; the other radioactivities will be less affected. The ^{41}Ca, ^{60}Fe, and ^{53}Mn are made well within the CO core of the supernova, and it is expected that following the explosion there will be a significant but unknown amount of fallback that may diminish the ejection of these three nuclides.

Ideally we would like to estimate the yield of ^{26}Al from the 60 $M_\odot$ supernova in a similar manner, but unfortunately the data have not been calculated and we must make a crude estimate. WLW give the ejected yields of the neighboring nuclei ^{24}Mg and ^{29}Si. The ratios of the yields of ^{26}Al to these two nuclei are given in Woosley & Weaver (1995) for the mass range 30–40 $M_\odot$, in which they vary only slightly. Using averages of these yield ratios and the WLW yields gives an estimated 60 $M_\odot$ supernova yield of about 3×10^{-4} $M_\odot$, with an uncertainty of an order of magnitude. To this yield must be added the yield of ^{26}Al expelled in the W-R wind from the 60 $M_\odot$ star. Chen, Gehrels, & Diehl (1995) note that there are theoretical expectations that W-R yields should range from 10^{-6} to 2×10^{-4} for the mass range 40–120 $M_\odot$, and they further note that at the upper limit a W-R star should give marginally detectable ^{26}Al decay gamma rays in the Vela region using COMPTEL. The gamma rays from such a W-R star were observed, and so we include an additional yield of 10^{-4} $M_\odot$ from the W-R wind of the 60 $M_\odot$ supernova. From these yields we obtain a ^{26}Al dilution factor for this supernova of 1.4×10^{5}.

The dilution factor can be translated into a geometric relation:

$$D = \frac{4\pi R^2}{\pi r^2},$$

where D is the dilution factor, r is the projected effective radius of the molecular cloud core, and R is the distance from the supernova to the core. As will become evident, we must solve for both r and R, so another relation is required. We will impose it in the form of an interesting range of shock velocities for the cloud core.

Boss (1995) has discussed the shock deformation and compression of a core with an asymptotic giant branch wind incident on it. He mentions that a shock wave from a distant supernova would have a similar behavior. He finds that a very substantial deformation of the side of the core nearest the supernova takes place, and that the shock progresses around the core before it has penetrated very far into the core itself. This surrounds the core with a hot dense gas and compresses it to the point of collapse under its self-gravity. The fresh radioactivities carried in the incident material are injected into the core and should become well mixed within it.

Let $v_{\rm ej}$ be the ejection velocity, $v_{\rm wr}$ be the W-R wind velocity, and $v_{\rm fin}$ be the final velocity of the material incident on the core. Let $M_{\rm ej}$ be the supernova ejected mass and $M_{\rm wr}$ be the total mass of the W-R wind. Let n be the average number density of molecules between the supernova and the core. Since the initial velocity is much higher than the final velocity the amount of mass in the ejecta will be much smaller than that in the swept-up gas. Then with momentum conservation, the distance from the supernova of the thick swept-up shell becomes (with all units in cgs):

$$R = \left[\frac{6.25 \times 10^{22} (M_{\rm ej} v_{\rm ej} + M_{\rm wr} v_{\rm wr})}{n v_{\rm fin}}\right]^{1/3} .$$

Table 2 shows the relevant quantities involved in the calculation of the distances between the supernova explosions and the molecular cloud cores that are struck by the supernova ejecta together with the swept-up intervening material (including the W-R wind, if any). These values are chosen to give the required ^{26}Al dilution at the time the swept-up shell has been slowed to a reasonable shock speed. There are four cases involving two supernova masses and two final shock velocities corresponding to the range considered by Boss (1995). The radius of a core is not well defined; the density of the gas in the core falls off smoothly until it merges with the background. If we take the radius of the core here to be the distance at which the density has fallen to 10^4 cm^{-3}, then we would expect the radius so defined to be about 3×10^{17} cm in a “massive” cloud core as is observed in the Orion A and B clouds (Harju, Walmsley, & Wouterlout 1993; Caselli & Myers 1995). The derived core radii in Table 2 are significantly smaller.

It is striking from the results shown in Table 2 that the distance from the supernova to the core is just a few parsecs. The supernovae considered are unlikely during their lifetime to wander very far from their point of formation in the cloud, so these small distances are reasonable (and it is simple to see from the second equation the effects of varying the gas density along the path length to the core). The impact radius of the shock is significantly less than the conventional core radius, which is reasonable since the low-density material in the outer part of the core will be swept away outside a cylinder defined by the projected radius r. The incident material within the cylinder defined by this projected radius will be injected into and mixed with the core. The heating of the gas around the periphery of the core and the resulting compression are suitable subjects for more study.

§4. DISCUSSION

Cosmic rays are usually considered to be accelerated by magnetic fields in hydrodynamically active regions, in which kinetic energy of mass motions can be transferred magnetically into particle energies. Thus it is understandable that the Orion phenomena of gamma rays and an excess carbon and oxygen low-energy cosmic-ray flux should be interpreted as a common property of star formation regions. However, our analysis suggests an attractive alternative that may provide a more consistent picture. These phenomena may be direct consequences of the supernova explosions themselves, and thus must be limited in time, but may also be episodic when new explosions occur.

The lifetime of interstellar molecular clouds, not counting formation times, is 1–3 × 10^7 yr according to the ages of the oldest T Tauri stars projected on clouds with visual extinction greater than 1 mag (e.g., Walter et al. 1988), or according to ages of OB associations with associated molecular gas (Blaauw 1991), and so the massive stars formed within such a cloud only reach the supernova stage for masses possibly as low as 9 $M_\odot$ during the lifetime of the cloud. Only a subset of these explosions can eject very energetic carbon and oxygen ions as Type Ib supernovae, so the distinctive pattern of the deexcitation gamma rays from these ions must also be quite rare, and the lifetime of the gamma-ray emission is likely to be only a few thousand years. The *Compton Gamma Ray Observatory* was apparently fortunately launched at a time when the nearest major star-forming region was host to such an event.

Our analysis of the injection of short-lived radioactivities into molecular cloud cores situated close (a few parsecs) to supernova explosions indicates that such injection should occur in a significant fraction of the cores in a molecular cloud and the actual level of the radioactivities found in a resulting planetary system should be quite variable. Already for ^{129}I in the solar system, with a mean life of 2.3 × 10^7 yr, the source appears to have been distant *r*-process–producing supernovae (Cameron 1993; Cameron, Thielemann, & Cowan 1993) near 10 $M_\odot$, and thus on its timescale a significant general background abundance level of such radioactivities appears to exist in molecular clouds and will become part of the cores that are formed.

The supernova ejecta may become well mixed within the core that it has impacted, but nevertheless, this can leave the grains in the core with a new set of isotopic anomalies. The condensible atoms within the core prior to the arrival of the shock wave are already condensed. After compression and admixture of the swept-up interstellar medium and diluted supernova ejecta, that admixed material will also chemically attach, but in this case to the surfaces of the preexisting grains. In the face of a size spectrum for that dust, the smallest dust will generally become most enriched (per unit mass) in the diluted supernova ejecta. These differing isotopic patterns fingerprint the subsequent chemical rearrangements as a form of chemical memory (Clayton 1982).

We have concluded that the core giving rise to the solar system was situated approximately in the range 2–10 pc from the site of a massive supernova explosion in the parent molecular cloud. A typical core in a cloud containing OB associations would lie somewhat farther away from the site of the association, but within the cloud lifetime the O stars can travel significant distances into the cloud before exploding; so the event we have described may be somewhat unusual, but it should not be rare. Even at larger distances the more gentle injection of ^{26}Al into a core should be common. However, a majority of cores that form stars are not subjected to quite such violent hydrodynamics resulting from this deformation and injection as appears to have been the case for the Sun, and it is important that the special character of this type of event should receive further study.

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TABLES

TABLE 1

QUANTITIES RELEVANT TO THE ABUNDANCES OF FOUR EXTINCT RADIONUCLIDES IN A 25 $M_\odot$ SUPERNOVA AND IN THE SOLAR SYSTEM

Quantity	^{41}Ca [a]	^{26}Al [b]	^{60}Fe [c]	^{53}Mn [d]
1. Mean life (yr)...	1.50×10^{5}	1.07×10^{6}	2.2×10^{6}	5.3×10^{6}
2. Reference nuclide...	^{40}Ca	^{27}Al	^{56}Fe	^{55}Mn
3. Reference abundance $(M_\odot)$...	5.99×10^{-5}	5.81×10^{-5}	1.17×10^{-3}	1.33×10^{-5}
4. Abundance ratio...	1.5×10^{-8}	5×10^{-5}	3.9×10^{-9}	1.3×10^{-6}
5. Radionuclide abundance $(M_\odot)$...	9.0×10^{-13}	2.9×10^{-9}	4.6×10^{-12}	1.7×10^{-11}
6. Supernova yield $(M_\odot)$...	2.0×10^{-5}	1.3×10^{-4}	2.1×10^{-5}	3.6×10^{-4}
7. Dilution factor...	2.2×10^{7}	4.3×10^{4}	4.5×10^{5}	3.6×10^{6}

NOTE.— See the text for a discussion of the quantities in the rows of the table. References for the abundance ratios are given in the footnotes.

[a] Srinivasan, Ulyanov, & Goswami 1994.

[b] Lee, Papanastassiou, & Wassenburg 1977.

[c] Lugmair, Shokulyukov, & MacIsaac 1995.

[d] G. W. Lugmair 1995, private communication.

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TABLE 2

QUANTITIES RELEVANT TO CALCULATION OF THE DISTANCES BETWEEN SUPERNOVAE AND CLOUD CORES STRUCK BY THE SHOCK WAVE

Quantity	25 $M_\odot$	25 $M_\odot$	60 $M_\odot$	60 $M_\odot$
Dilution factor...	4.3×10^4	4.3×10^4	1.4×10^5	1.4×10^5
M_{ej} ($M_\odot$)...	10	10	3	3
M_{WR} ($M_\odot$) ...	0	0	50	50
v_{ej} (cm s^{-1}...	1×10^9	1×10^9	1×10^9	1×10^9
v_{WR} (cm s^{-1} ...	0	0	3×10^8	3×10^8
v_{fin} (cm s^{-1}...	2.5×10^6	1.0×10^6	2.5×10^6	1.0×10^6
Distance R (cm)...	7.9×10^{18}	1.1×10^{19}	2.2×10^{19}	2.9×10^{19}
Core radius r (cm)...	7.6×10^{16}	1.0×10^{17}	1.1×10^{17}	1.6×10^{17}

NOTE.— Calculations are for the two supernova masses and different choices of the final shock velocity v_{fin}. In all cases the density of the material in the molecular cloud is taken to be 10^3 cm^{-3}.

Image of typeset table (9kb) | Discussion in text
