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Implications of the Broad 26A1 1809 keV Line Observed by GRIS

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IMPLICATIONS OF THE BROAD ^{26}Al 1809 KEV LINE OBSERVED BY GRIS

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ABSTRACT

The surprisingly large width of the 1809 keV γ-ray line from decay of radioactive ^{26}Al, recently observed by GRIS (Naya *et al.* 1996), has profound astrophysical implications. While there may be no apparent, single mechanism that can explain the observed broadening, we identify high speed dust grains, extremely hot superbubbles, and a large, low density, gaseous halo in the Galactic center region as the possible origins and discuss their intriguing revelation of the hot gas content in the ISM.

Keywords: nucleosynthesis; supernova remnants; interstellar medium; dust grains; Galactic halo.

1. INTRODUCTION

In a recent balloon flight, the Gamma Ray Imaging Spectrometer (GRIS) experiment, with a large field of view of $\sim 100°$, drift-scanned the Galactic center (GC) and detected the 1809 keV line with a flux of $(4.8\pm0.7)\cdot10^{-4}$ ph s^{-1} cm^{-2} rad^{-1} (6.8σ). The line profile, however, is surprisingly broad with a FWHM of 6.4 ± 1.2 keV, which, after removing the instrumental line width of 3.4 keV, gives an intrinsic FWHM of W=5.4±1.4 keV (Naya *et al.* 1996).

The great impact of the GRIS results is that the reported broad line, if confirmed, posts a big challenge to our understanding of ^{26}Al production and propagation in the Galaxy. It has never been anticipated that ^{26}Al could be so hot or move so fast in the interstellar medium (ISM) for much of its 10^6-yr lifetime, although an earlier GRIS flight had shown a hint of a broadened line (Teegarden *et al.* 1991). On the other hand, the GRIS line width is consistent only at the 7% level with the 3 keV upper limit obtained by *HEAO* C-1 (Mahoney *et al.* 1984; Naya *et al.* 1997), which had a similar energy resolution and saw a similar flux at 4.8σ level. We note that GRIS has about twice the FOV of *HEAO* C-1 and a much simpler background subtraction procedure. Future measurements by the *INTEGRAL* shall resolve this discrepancy.

2. GENERAL CONSIDERATIONS

The 1809 keV line width observed by GRIS requires a Doppler velocity of $v \sim 540 \pm 140$ (W/5.4 keV) km s^{-1} for a spherical expansion, or an effective Doppler temperature of $T \sim (4.5 \pm 2.3) \cdot 10^8$ $(W/5.4 \text{ keV})^2$ °K (or equivalently, $kT \sim 39 \pm 20$ keV) for a thermal origin. This line was previously expected to be much narrower, exhibiting only a velocity typical of Galactic differential rotation or of random motions in the ISM (Ramaty & Lingenfelter 1977; Skibo & Ramaty 1991; Gehrels & Chen 1996). By assuming an ^{26}Al source distribution following that of free electrons (Taylor & Cordes 1993; Prantzos 1993; Chen, Gehrels, & Diehl 1995), and adopting an empirical Galactic rotation curve (Brand & Blitz 1993), we find that the Galactic rotation would produce a line width of ≤ 1.7 keV FWHM in the field of view of GRIS, which is 3–4 times smaller than the observed value.

New line broadening mechanisms are thus required. But first we test if a narrow component can be "hidden" in the line observed by GRIS by fitting the data with two Gaussians of different widths, both centered at 1808.7 keV. The narrow component has a fixed FWHM of 1.7 keV. The total line intensity, the width of the broad component and the intensity fraction of the narrow line, $0\leq f\leq1$, are free parameters in the fits. The data set consists of 100 energy channels of 1 keV wide, covering the line and surrounding continuum. We find that the best fit is a single broad line (i.e., f=0) with an intensity of $1.5 \cdot 10^{-2}$ counts s^{-1} and an intrinsic width of 5.42 keV FWHM. For finite f, Table 1 shows that the fit gets worse as f increases. The difference between the minimum χ^2 at finite f and the best fit χ^2 at f=0 gives the variation of χ^2 values with one additional degree of freedom. The compatibility of these fits with the GRIS data is estimated as the probability of the χ^2 value distribution with one degree of freedom, listed in the last column of Table 1. A narrow line having 50% of the flux has an occurrence probability of only 4.2%. Therefore, we require that for any mechanism to explain the GRIS data, it has to be able to produce a line width of at least 4 keV for at least 50% of the total flux. In other words, it has to keep the ^{26}Al moving at v>400 km s^{-1} or in a hot region of T>$2\cdot10^8$ °K (kT>20 keV) for at least $7\cdot10^5$ yrs.

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Table 1. Compatibility of the GRIS data with a narrow line contribution f

f	Intensity counts s^{-1}	FWHM keV	χ^2	$\Delta\chi^2$	Prob.
0.0	0.0150	5.42	103.17		
0.1	0.0147	5.50	103.84	0.67	0.4135
0.3	0.0142	6.20	105.37	2.20	0.1389
0.5	0.0132	6.62	107.27	4.10	0.0425
0.7	0.0118	6.99	109.40	6.23	0.0128
0.9	0.0106	6.89	111.56	8.39	0.0037

3. THERMAL BROADENING

Although ^{26}Al is usually synthesized in a very hot environment, such as in core-collapse supernovae (SNII) and novae, or inside AGB or massive stars (e.g., Prantzos & Diehl 1996), the temperature at the ^{26}Al birth sites is not relevant to the observed line width because of low stellar surface temperature or fast adiabatic cooling after explosions. Thermal broadening may produce the observed GRIS line width only if the ^{26}Al can be *reheated* to a few 10^8 °K after ejection and the cooling time of the hot region is longer than a few 10^5 yrs.

The only place such reheating may take place is behind a shock front. The post-shock temperature, $T_s \sim 2.3{\cdot}10^7\,\mu\, v_{s,3}^2$ °K, may reach $2\cdot10^8$ °K in cases of a large shock speed $v_{s,3}{=}v_s/10^3$ km s^{-1}, or a gas containing mainly heavy metals with a large mean atomic number $\mu = m/m_H$, or both. It is obvious that such conditions may exist with long time scale only in young supernova remnants (SNRs), where strong shocks are formed as the blast wave runs into the ISM. Although the forward shock can have a post-shock temperature of $>10^9$ °K early on when its speed is $>10^4$ km s^{-1}, it will be slowed down to 10^3 km s^{-1} in just $3.1{\cdot}10^3\, E_{51}^{1/3} n_0^{-1/3} v_{s,3}^{-3/5}$ yrs, where $E_{51}{=}E/10^{51}$ ergs is the SNII kinetic energy, n_0 is the number density of the ISM. More importantly, the hot post-shock region is filled mostly by the ISM gas swept up by the shock which contains little ^{26}Al.

On the other hand, a reverse shock will form and run back into the ejecta due to the high pressure in the post forward-shock region (McKee 1974). The current SNII model (Woosley & Weaver 1995) places most ^{26}Al in the Ne-burning shell with an enclosed mass between 3 and 5 $M_\odot$ (see also Timmes *et al.* 1995). Applying the reverse shock model of McKee & Truelove (1995) to a 25$M_\odot$ SNII with an ejecta mass of 23 $M_\odot$, we find that the ^{26}Al layer will meet the reverse shock at a time between 1.35 and 2.13 t_{ST}, where $t_{ST}{=}1.4{\cdot}10^3\, E_{51}^{-1/2}\, M_{e,20}^{5/6}\, n_0^{-1/3}$ yr is the characteristic time for the onset of the Sedov-Taylor phase of the SNR evolution and $M_{e,20}{=}M_e/20M_\odot$ is the mass of the ejecta. The peak shock temperature in the ^{26}Al layer can reach 0.17 to 0.19 T_{ST} or $\sim 4{\cdot}10^7$ °K, where $T_{ST}{=}2.4{\cdot}10^8\, E_{51} M_{e,20}^{-1}(\mu/1.8)$ °K. Therefore, the reverse shock temperature is usually not high enough to account for the observed GRIS line width, unless E_{51} is greater than 5 or the ^{26}Al is confined in a narrower and deeper layer so that it can be shocked at a much later time to reach a higher post-shock temperature.

Observationally, a 10^8 °K plasma heated by the *reverse shock* has yet to be seen from any SNR. In the joint *Ginga-ROSAT* spectrum of IC443, a very hot (13 keV) component with probably a large spatial extent and low surface brightness is identified along with the normal, soft ($T{\sim}1$ keV) component (Asaoka & Aschenbach 1994). We do not know where exactly the hot gas is located, although the age of IC443, $\sim10^3$ yrs, is in the right range for a strong reverse shock. However, a nearby, newly discovered SNR of larger size and 10^5 yrs age shows no sign of the hot component (Asaoka & Aschenbach 1994), indicating either a short lifetime or a very low surface brightness.

Even if the desired temperature can be reached, to prevent severe adiabatic cooling the shocked gas has to stop expanding, i.e., its velocity <10 km s^{-1}. This implies the existence of a region of a few pc in size in the central portion of the SNRs, filled with hot gas for which bremsstrahlung radiation is the main cooling mechanism. This hot gas may stay hot for as long as $\tau_c{\sim}5.3{\cdot}10^5\, T_8^{1/2}\, R_{pc}^3$ yr. In reality, large scale mixing of the ejecta with the ISM gas swept up by the forward shock may occur when the SNR expansion is significantly slowed down, thus greatly reduce the survival time of the central hot region, but this may be hard to tell from observations.

When a large number SNIIs exploded in a relatively small volume, an extremely hot superbubble may be created. At the Galactic center (GC), *Ginga* observations found a region of 270 pc by 150 pc in size with a temperature of ∼10−15 keV, an electron density of 0.03−0.06 cm^{-3}, a total thermal content of $(4{-}8){\cdot}10^{53}$ ergs, and a cooling time on the order of 10^9 yrs (Yamauchi *et al.* 1990). Such places would be ideal for the hot ^{26}Al if the temperature were a factor of 2 higher. The hot gas-^{26}Al connection has been proposed previously (von Ballmoos 1991) but the hot gas spatial distribution is different from the COMPTEL map (Diehl *et al.* 1995). For the GC region at least, this component cannot be ruled out.

However, it is not easy form a superbubble as hot as the GC bubble case. Studies of superbubbles (e.g., Serabyn & Morris 1995, and references therein) suggest that bubble interior temperature evolves with time as, $T(t){\sim}5\cdot10^6\, L_{38}^{8/35}\, n_0^{2/35}\, t^{-3/35}$ °K, where L_{38} is the energy input in units of 10^{38} ergs s^{-1} which corresponds to about 100 SNIIs in 10^7 yrs. The temperatures required by the GRIS data could be achieved only in dense regions that have experienced 10^3 or more SNIIs in the last 10^7 yrs, as is the case for the GC superbubble. For SNIIs exploding uniformly in time, the amount of observable ^{26}Al in such a bubble is $\sim10^{-4}M_\odot{\cdot}10^2 \sim 0.01M_\odot$. To account for the 1−3 $M_\odot$ of observed ^{26}Al (Diehl *et al.* 1995), we need 100−300 such starburst regions in the inner Galaxy. This number implies an SNII rate of one per 33 to 100 yrs, about the same as the *total* SNII rate for the entire Galaxy, i.e., almost all the SNIIs exploded in the last 10^6 years have to be inside one of these superbubbles. This is probably not the case given our knowledge of the current distribution of Galactic OB associations. On the other hand, the required superbubble density also implies a volume filling factor of 13% for an inner Galaxy of 5 kpc in radius and 400 pc in thickness. If the massive star formation region, including the spiral arms, the molecular ring and the GC bar, occupies ∼20% of the total volume of the inner Galaxy, the superbubble filling factor is then 65%. While studies of star forming patterns in other spiral galaxies (Elmegreen & Efremov 1996) clearly suggest that fresh ^{26}Al could be distributed inhomogeneously on scales ∼ 1 kpc, it is not clear that the youngest star forming regions are all confined to superbubble structures. In fact, only few such shells are observed in the Galactic disk, although this could be due to selection effects.

4. KINETIC BROADENING

Except AGB stars, ^{26}Al ejected from all other sources has an initial speed of >1000 km s^{-1}. The minimum requirement to fit the GRIS data, however, asks for the ^{26}Al to fly at ~400 km s^{-1} for $7{\cdot}10^5$ yrs (§ 2), i.e., a minimum expansion radius of 280 pc. A greater average expansion speed gives an even bigger size. This is certainly much greater than the remnant sizes of most novae, W-R stars, single SNRs, and even many superbubbles. One way to get around this is to argue that much of the emission may come from a foreground SNR so that the freshly synthesized ^{26}Al is still moving fast and the actual size of the SNR is not too big. The best candidate for this hypothesis is Loop I in the Sco-Cen association, which has an angular diameter of 116° centered at 170 pc from the Sun and has been suggested to be the source of 1809 keV emission (Blake & Dearborn 1989). Recent *ROSAT* and radio observations suggest a mean rate of 2 SNIIs per 10^6 yrs in the Sco-Cen association and indicate that the latest SNII may have occurred $\sim 2{\cdot}10^5$ yrs ago with a progenitor mass of 15−20 $M_\odot$ (Egger 1993). To study the compatibility of the GRIS data with an emission from Loop I, we have calculated the expected 1809 keV line rate for such a distribution. We find that Loop I could not be the main source of the observed 1809 keV line because it would cause a 3-hr shift between the predicted and observed maximum rates in the GRIS scan and require a total of 10^{-3} $M_\odot$ of ^{26}Al to account for the observed intensity, which is one order of magnitude higher than the expected from the SN rate inferred from the observations (Egger 1993; del Rio *et al.* 1994).

We consider two alternatives, a large scale gaseous hot halo in GC and high speed dust grains. The possibility of a GC halo containing a large fraction of the observed fast ^{26}Al stems from two aspects. First, global ISM models for disk galaxies (Heiles 1990; Rosen & Bregman 1995) indicate that a large fraction of the medium may reside in a network of connected bubbles. Occasionally the bubbles break out of the disk with velocities as high as ~400 km s^{-1}. The ^{26}Al produced by generations of SNIIs and sufficiently mixed with the outflowing gas may give rise to the observed broad line. The most probable place such scenario may be realized is in the GC region, where an intense starburst involving $\geq 10^5$ SNIIs is proposed to have occurred $\sim 1.5{\cdot}10^7$ yrs ago (Sofue 1994; Hartmann 1996; Hartmann, Timmes, & Diehl 1996). The starburst may produce the observed 1809 keV line flux, however, only if it is continuous instead of impulsive so that at least 10% of the 10^5 SNIIs actually exploded within the last 10^6 yrs. Recently, the existence of such a starburst is under questioning from analysis of the *ROSAT* all-sky survey data (Snowden *et al.* 1997). The X-ray emission that can be definitively attributed to the GC region is found to be from roughly a cylinder of tenuous hot gas, $n_e \sim 0.003$ cm^{-3} and $T_e \sim 10^6$ °K, with a radius of 5.6 kpc and a scale height of 1.9 kpc. The more extended emission features previously included as part of a supershell are probably due to foreground sources. The thermal content in the *ROSAT* halo gas is $6{\cdot}10^{55}$ ergs, which is a factor of 2−3 less than the total energy estimated for the proposed starburst. While this energy still requires $(3-6){\cdot}10^4$ SNIIs, we cannot tell if it is the result of a starburst over the last 10^7 yrs or of the continuous energy input from the disk in the last $>10^8$ yrs, i.e., over the bremsstrahlung cooling time of the halo. If it is the latter, the total amount of currently observable ^{26}Al will be negligible.

Another alternative is to use high speed dust grains. This is prompted by the fact that dust grains could form efficiently within a few years of an SNII explosion, as seen in SN 1987A (Bouchet, Danziger, & Lucy 1991), and thus inherit a large expansion velocity of $\geq 10^3$ km s^{-1}. Because of their large masses, $>10^3$ amu, these high speed grains could travel through the SNR ballistically and survive in the ISM for a long time, i.e., their expansion is not limited by the size of its SNR. It is conceivable that a substantial fraction of ^{26}Al is attached to dust grains.

To calculate the lifetime of the fast grains in the ISM, we assume that dust grains formed in SNRs have a radius $a \leq 100$ Å (Dwek 1988) and density $\rho_g \sim 3$ g cm^{-3}, i.e., a mass of $m_g \leq 1.2{\cdot}10^{-17}$ g or $7.5{\cdot}10^6$ amu. Moving at a speed v_g in the ISM, the dust grains suffer a drag force, $F_d = \pi a_g^2 n_0 m_H v_g^2$, due to collisions with ISM particles (Dwek & Arendt 1992). Because of their low charge-to-mass ratio, the effects of small angle Coulomb scattering is negligible. The grains will then lose half of their original speed in $t_{1/2} = 4a\rho_g/(3n_0 m_H v_g)$ or $1.1{\cdot}10^3$ $a_2 n_0^{-1} v_{g,5}^{-1}$ yr, where $a_2 = a/10^2$Å, $v_{g,5} = v_g/500$ km s^{-1}. Therefore, to survive for more than 10^5 yrs requires either a much larger grain size, $a \sim 0.1-1$ μm, or a very low density medium, $n_0 < 0.01$ cm^{-3}.

The distribution of grain sizes in the ISM is approximately a power law with an exponent of about −3.3 to −3.6 (Mathis, Rumpl, & Nordsieck 1977; Mathis & Whiffen 1989), while for graphite the sizes range from 0.005 to 1 μm and for other materials from 0.025 to 0.25 μm. Therefore, dust grains larger than 0.1 μm are rare in nature. Our only other alternative is then to inject the high speed dust grains into a low density medium of, again, a minimum 560 pc in diameter. This low density medium is likely to be hot, $T \sim 10^6$ °K, so the possibility of dust evaporation has to be considered. If the grains containing ^{26}Al are much larger than 10Å, the average vaporization time due to absorbtion of 0.1−1 keV photons will be much longer than the dust cooling time (Dwek 1988), i.e., the grains are stable against X-ray evaporation and, by the same token, collisional heating by ISM gas at a relative speed of 500 km s^{-1}. Another way to destroy dust grains is by kinetic sputtering in which atoms on the grain surface can be stripped off by the impact of energetic particles during collision, since the binding energy on the grain surface is only a few eV (Dwek & Arendt 1992). While the physics of sputtering yield, especially for light ions near the energy threshold, are still uncertain, a simple estimate of the grain lifetime against sputtering at temperatures $\geq 10^6$ °K is $\tau_{sp} \sim 2{\cdot}10^4$ $a_2\, n_0^{-1}$ yr (Draine & Salpeter 1979). The lifetime for grains moving at 500 km s^{-1} in such a hot gas is probably of the same order, since the incoming ions have about the same kinetic energy is their thermal energy. It is thus safe to say that the sputtering lifetime of the high speed grains in a low density ($n_0 <$ 0.01 cm^{-3}) medium is similar to the ^{26}Al lifetime.

5. DISCUSSIONS

We have shown that there seems at present no definitive answer to the question of which physical mechanism actually produced the large width of the 1809 keV line observed by GRIS. It is clear, however, that the observed broadening is probably not of thermal origin, although a thermal component may contribute some fraction of the observed flux with a FWHM of ~3 keV. The kinetic broadening, on the other hand, could be due to either long-lasting, fast expansion of SNII ejecta or high speed dust grains which may form in the ejecta. The most important point is that both these schemes require the existence of a large (∼500 pc), low density ($n<10^{-2}$ cm^{-3}) environment. This result is robust because it is derived from the basic physical principles of the spectral line formation and gas-particle interactions. Where to find such low density medium touches some fundamental questions about the general ISM conditions in the Galaxy.

For the high speed dust grains to survive in a random location on the spiral arms, the required low density environment has to not only have a volume filling factor of at least 50% but also consist of mostly large sized bubbles. Although such a picture fits the classical theory of McKee & Ostriker (1977), it seems to be at odds with the current trend in ISM modeling (e.g., Cox 1995). Alternatively, we may look for the low density medium *only* in the GC direction, since this is where GRIS detected the broad line and *ROSAT* saw the hot halo. If a low density medium permeates most of the volume of the inner Galaxy, the ^{26}Al produced in it will be able to acquire and keep high velocities either by riding on high speed dust grains or simply by moving along with the ever expanding SNII ejecta in the hot halo. An important point is that the sources which created the hot halo gas are not necessarily the same ones which produced the observed ^{26}Al. The hot gas could be the result of either a burst of massive stars and their SNIIs in the disk or a steady state energy input which involves Type Ia SNs and novae in the Galactic bulge as well. The current star formation rate in the inner 200 pc of the GC, $\sim 0.5\ M_\odot$ yr^{-1} (Morris & Serabyn 1996), is too small to produce either the halo or much of the observed ^{26}Al.

It is hence intriguing to learn that the correct answer to the origin of the broad 1809 keV line observed by GRIS will have penetrating implications to our view of not only the Galactic ^{26}Al production but also the ISM conditions along the spiral arms and in the inner Galaxy. Future γ-ray mission such as *INTEGRAL* will have enough spatial and spectral resolution to pin down where this broad component comes from and provide information of the ISM currently not obtainable by any other means. If it sees a broad line from everywhere on the Galactic plane, a large volume filling factor of hot thin gas is implicated and high speed dust grains are the most probable source. Variations in line width and intensity will reveal the distribution of this parameter along the plane. If, on the other hand, *INTEGRAL* only sees the broad line from the GC direction, the existence of a large scale, low density, hot gaseous halo is inevitable. Its origin, energy source, and theoretical and observational consequences at other wavelengthes will then have to be studied.

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