Mapping Galactic ^{60}Fe synthesis in Centaurus-Circinus

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Abstract

We propose 1,500 ks SPI observations of the Cen-Cir region [l,b = 310^o, 0^o] to detect γ-ray lines from ^{60}Fe. This project was partly carried out in AO-1. We request AO-2 observations to reach the original exposure. Recently RHESSI detected ^{60}Fe lines from the inner Galaxy (l = 0^o ± 30^o) with a combined lines flux of F = (0.9 ± 0.3) 10^{-4} γ cm^{-2} s^{-1}. Thus our original INTEGRAL exposure time estimate is now firmly based on observations instead of theoretical estimates.

The Cen-Cir region was observed under project No. 012 0158 during revolutions 89 to 92 (see Table). At the time of submission of this proposal data have not been received at the PI institution, so that no analysis has yet been carried out. The current data set amounts to a total SPI exposure time of 509.65 ks, which is to be compared to the AO-1 request of 2,000 ks.

Revolution	89	90	91	92
Exposure (ks)	3.467	142.147	187.218	176.817

Scientific Objectives and Recent Developments

^{60}Fe is thought to be solely the product of core collapse supernovae, and theoretical yields suggested line fluxes near the upper limits from SMM, COMPTEL, and GRIS. Detection and mapping of ^{60}Fe is a key objective in γ-ray astronomy. RHESSI recently detected the diffuse glow of ^{60}Fe near the predicted level (Smith 2003b), and we expect INTEGRAL to confirm this detection and to advance ^{60}Fe science through a resolved map.

^{60}Fe is co-produced in core-collapse supernovae (SNII) with ^{26}Al, which was mapped in detail with COMPTEL and is currently mapped with better sensitivity and resolution with INTEGRAL. The origin of ^{26}Al itself is still not clear, but production in SNII and WR stars is thought to exceed contributions from novae and AGB stars. Maps of the Galaxy in γ-ray lines from ^{60}Fe would provide an estimate of the relative importance of SNII for the origin of the ~2 $M_\odot$ of ^{26}Al present in the Milky Way. Key objective of ^{60}Fe and ^{26}Al mapping with INTEGRAL is thus a correlation study of these two isotopes.

If the lines are strong enough for a shape measurement, we learn valuable lessons about the average bulk or thermal speeds of the decaying nuclei. The discovery of "hot" ^{26}Al by GRIS (Naya et al. 1996) was a serious challenge for theoretical models of the production and dissemination of ^{26}Al, but recent RHESSI observations (Smith 2003a) show that the line width is smaller than that inferred from the GRIS data. However, the line is broader than expected from Doppler shifts due to Galactic rotation. Recently, Kretschmer, Diehl, and Hartmann (2003) show that "warm" ^{26}Al can in fact be understood in terms of the early evolution of the radioactive debris in supernova remnants. Thus key objectives for INTEGRAL studies of ^{60}Fe include a determination of the "temperature" of this isotope and a comparison of line shapes with those found for aluminum.

Cen-Cir observations complement the deep inner galaxy exposure and the Cygnus/Vela pointing in the core program. **Maps** will provide a measure of galaxy-wide star formation not attainable with other methods. The AO-1 Cen-Cir observations constitute 25% of the requested exposure, but there was no guarantee that even the requested 2,000 ks would be sufficient to detect ^{60}Fe, as the estimated yields were just that - estimates. The RHESSI detection provides a solid base for the expectation that we will detect ^{60}Fe with SPI, and that INTEGRAL is on its way to produce a map. Cen-Cir observations will contribute to the goal of covering the galactic plane deeply, especially in areas of known strong 1.8 MeV emission.

1. Scientific Justification

"Astronomy with Radioactivities" (Arnould & Prantzos 1999; Clayton 1982, 2003; Diehl & Timmes 1998; Diehl & Hartmann 1999; Prantzos 2002; Diehl, Hartmann, et al. 2002, 2004) derives from a significant list of isotopes, each providing a probe of unique aspects of element synthesis. Among the only recently detected species is ^{60}Fe, which emits two γ-ray lines at 1173 keV & 1332 keV. ^{60}Fe is produced predominantly in SNII with a typical yield of a few times 10^{-5} $M_\odot$. With a lifetime of 2.2 million years the steady state abundance of ^{60}Fe in the MW is of order 2 $M_\odot$, assuming an event rate of a few per century. If the ^{26}Al is due to massive stars, γ-ray lines from ^{60}Fe trace the 1.809 MeV map. Figure 1 shows the observed 1.809 MeV ^{26}Al map from COMPTEL (right), together with the line measurements of ^{60}Fe with RHESSI (Smith 2003b). The RHESSI data are obtained from the range l = -30^o to +30^o, and b = -5^o to +5^o, where the COMPTEL map indicates the bulk of the emission.

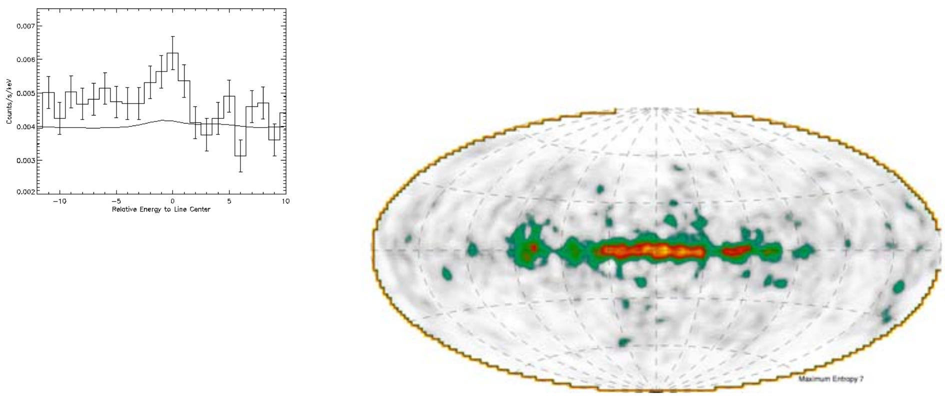

Fig. 1: [Left] ^{60}Fe line (RHESSI, Smith 2003b), [Right] Observed ^{26}Al map at 1809 keV (COMPTEL; Diehl & Oberlack 1997)

Clayton (1971) predicted line fluxes of at least 10^{-5} photons/cm^2 s from the inner galaxy, while later studies (Ramaty & Lingenfelter 1977) suggested values more than one order of magnitude larger. Observations with SMM (Leising & Share 1994) placed an upper limit of 8x10^{-5} γ/cm^2 s radian on the flux, and GRIS (Naya et al., 1998) gave a similar constraint. Theoretical estimates of supernova yields (e.g., Timmes et al. 1995) suggested that the line fluxes should be ~ 15% of the flux at 1.809 MeV. Based on these estimates we proposed in AO-1 to observe Cen-Cir for 2x10^6 s, adding exposure to the effort within the core program. 25 percent of the requested observation time was obtained in AO-1.

The study of gamma-ray lines from ^{60}Fe is intimately connected to the diffuse 1809 keV line from radioactive ^{26}Al, discovered by HEAO-3 (Mahoney et al. 1984) and has since been mapped in great detail by COMPTEL (e.g., Prantzos & Diehl 1996). The line-image of our Milky Way (Figure 1) shows clearly that the bulk of ^{26}Al is produced in the inner Galaxy, consistent with the known star formation pattern. Some regions stand out: Bulge, Vela, Cygnus, Cen-Cir, Carina. The amount of ^{26}Al in the ISM corresponding to the observed flux is ~2±1 $M_\odot$. Supernovae eject of order 10^{-4} $M_\odot$ of ^{26}Al, where the yield varies by one order of magnitude for stars in the 10-40 $M_\odot$ range (e.g., Timmes et al. 1995). With a mean life of ~ 10^6 yrs and a rate of ~1-3 events/century the observed flux can be accounted for by supernovae. Timmes et al. (1995) provided yields for ^{60}Fe (Fig. 2), which lead to a predicted ^{26}Al/^{60}Fe line flux ratio of order 10 %-20%. This estimate was recently confirmed with RHESSI.

^{26}Al is produced by proton capture on ^{25}Mg, and destroyed by e^+ decay, and thermal (n, p), (n,α), and (p, n) reactions. Pre-SN synthesis occurs in the hydrogen burning shell. Part of the ^{26}Al is convectively transported into the red giant envelope, from where it can be ejected in a stellar wind. A larger amount of ^{26}Al is produced in the oxygen and neon burning shells (Weaver & Woosley 1995; Woosley, Heger, & Weaver 2002). The explosion ejects the outer regions unaltered, while shells closer to the core are shock heated, which results in an increased yield. The ν-flux boosts the yield. ^{26}Al is also produced in novae, WR winds, and AGB stars. The key question is the breakdown of ^{26}Al by source: how much of the observed ^{26}Al is due to each?

^{60}Fe is co-produced with ^{26}Al in the oxygen-neon burning shell. An additional component is from explosive burning at the bottom of the helium shell. This fact is of key importance for the angular distribution of their respective γ-ray lines and any line broadening due to transport. When the yields of ^{26}Al and ^{60}Fe are combined with a SN rate and folded with their respective life times, the predicted steady-state gamma-ray line flux ratio is 16% (Timmes et al. 1995). Woosley (1997) considered synthesis in rare carbon deflagration supernovae. If rare SNIa were responsible for a significant fraction of ^{60}Fe synthesis, the INTEGRAL map would not correlate well with the 1.809 MeV map. ^{60}Fe is also synthesized in AGB stars (Busso, Gallino, & Wasserburg 1999; Gallino et al. 1999), and WR stars (Arnould et al. 1997).

The nuclear reaction rates relevant to the synthesis of ^{26}Al and ^{60}Fe have not changed significantly since the work of Woosley & Weaver (1995) and Timmes et al. (1995). Woosley & Heger (1999) find an uncertainty of a factor 3. For ^{26}Al, calculations by Rauscher et al. (2002) and Chieffi & Limongi (2002) suggest agreement in the yields, but this is not the case for ^{60}Fe.

The map of ^{26}Al supports the idea that massive stars are responsible for most of the (steady-state) production of this species (Prantzos & Diehl 1996). Novae cannot contribute substantially, because if they did the observed flux distribution would be smoother and exhibit a different angular pattern. That leaves winds from AGB stars and very massive stars (WR, LBV stages) and core collapse supernovae to compete for the title of "top producer". If the relative contribution from these stars can be determined, the ^{26}Al data would provide a measure of the global Galactic star formation rate (Clayton et al. 1993; Timmes, et al. 1997). The contribution from AGB stars (1.5-6 $M_\odot$) was re-evaluated by Mowlavi & Meynet (2000), who find that AGB stars contribute less than 0.2 $M_\odot$ to ^{26}Al. Half of which is due to AGB stars with $M > 5\ M_\odot$.

A detailed comparison between the 1.809 MeV map and a large variety of all-sky maps that might provide a potential tracer of ^{26}Al production suggests a tight correlation between the γ-ray map and free-free emission at 53 GHz (Knödlseder, et al. 1999). The observed correlation supports the association of ^{26}Al with star formation activity. Although γ-ray line maps do not give direct information on the distance to the sources, INTEGRAL's improved sensitivity and angular resolution produces data that bear on the Galaxy-wide star formation pattern. Key issue in the interpretation of the data is the relative importance of ^{26}Al injection from WR/LBV winds and from stellar explosions.

Differential rotation of the Milky Way implies broadening of the line of order 1.5 keV (Gehrels & Chen 1996). The GRIS discovery of a line broadened by > 5 keV (Naya et al. 1996) was hard to explain (Chen et al. 1996, Naya et al. 1998; Sturner & Naya 1999). Aluminum would have to move either very fast (~ 500 km/s), which implies fast moving carrier particles that maintain large speeds for over a million years, or are embedded in a hot plasma (>10^8 K) which must be kept in this extreme condition for many million years. However, the RHESSI observations (Smith 2003a) of the central radian of the suggest a lower line width (FWHM = 2 ± 1 keV). Kretschmer, Diehl, & Hartmann simulated the kinematics of ^{26}Al including galactic differential rotation and expansion in supernova remnants, and find that ^{26}Al is still somewhat warmer than expected.

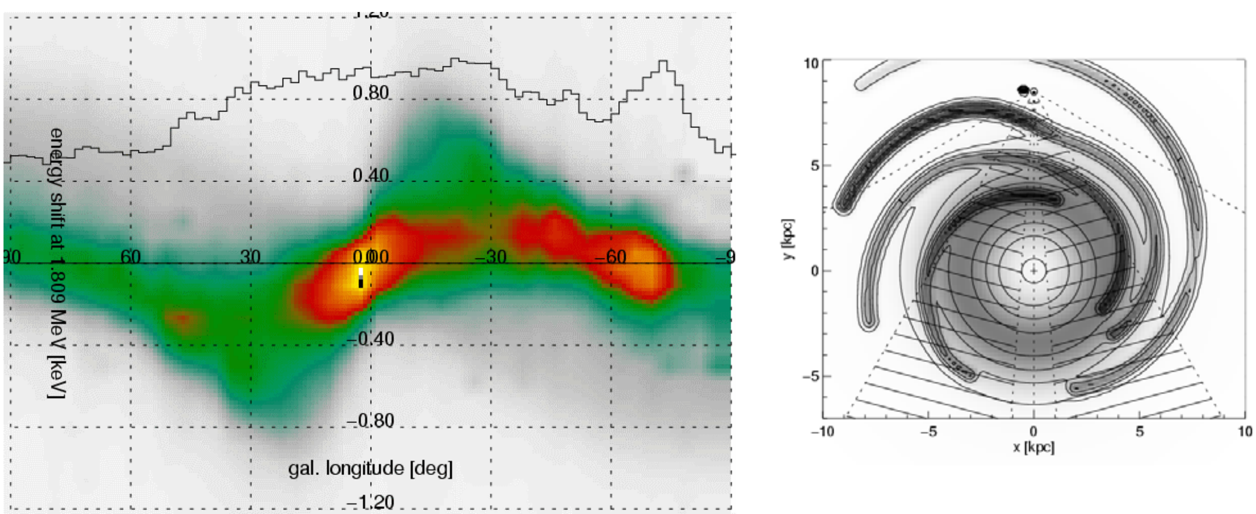

Fig 4: [Left] 1.809 MeV flux as a function of energy (relative to line center) vs longitude (Kretschmer et al. 2003). Integrating over ±30° yields a line width slightly smaller than observed with RHESSI. In the Cen-Cir region around l = 310° the predicted line width is below 1 keV. This simulation is based on the galactic electron density model [Right].

INTEGRAL will reveal whether or not the line width is the same everywhere. If the shape varies, the map provides valuable clues on the origin of ^{26}Al. Mapping of ^{60}Fe is recognized as top scientific goals of the INTEGRAL mission (Knödlseder & Vedrenne 2001), and so is the fact that it will take a large exposure to accomplish this goal.

3. Proposed Observations

In AO-1 we proposed a medium-deep (2 10^6 s) exposure of the Galactic plane in the Cen - Circ region, to detect γ-ray lines from ^{60}Fe. 25% of this time was carried out in AO-1. We resubmit this proposal to obtain the remaining time.

The reason for the pointing direction follows from the existing ^{26}Al map. We expect a similar sky distribution for ^{60}Fe and a line flux ratio 10-20%, supported by the RHESSI detection. The CP covers the inner +/-30 degrees, and also the Cygnus and Vela regions. This leaves the Cen-Cir region underexposed, despite the fact that the flux in this region is comparable to that in Cygnus and the Vela region. We thus propose to re-observe this field, centered on position (l,b) = (310^o,0^o). We used the COMPTEL 1809 keV map to determine the flux in the area l = 310^o ± 10^o and b = 0^o ± 10^o. ^{26}Al is detected in this area with a flux of **F(1809 keV) = 6 10^{-5} (γ/cm^{2}s).** Using the theoretical flux ratio of 16% (supported by the RHESSI result of 0.9 ± 0.3 γ/cm^{2}s per line vs.16% of 5.7 10^{-4} γ/cm^{2}s at 1.809 MeV in the same part of the sky) and combining the two iron lines, **the estimated total line flux is ~1.9 10^{-5} (γ/cm^{2}s)**. Assuming 0.5 keV FWHM and S/N=3, the OTE returns an exposure time of~ 2000 ks. Our simulations of galactic rotation and outflow dynamics (Kretschmer et al. 2003) suggest a FWHM of less than 1.0 keV at this position along the plane. The gamma-ray background lines in the SPI Ge detector spectra (Wunderer et al. 2003) suggests that we need S/N > 3 as a minimum. **Thus we request 1,500 ks to be carried out during AO-2**.

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