INTEGRAL AO-1 Proposal
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Scientific Justification

Title: Extension of Galactic Centre Deep Exposure

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Introduction.

The INTEGRAL Core Program includes two surveys which can be used to address large-scale Galactic structure: the GCDE and the GPS. The GCDE is a deep survey of the inner 60^o of the Galactic plane, with an exposure of 4.3 10^6 s per year, and the GPS is a shallow survey of the entire plane with an exposure of 2.3 10^6 s per year. The GPS is designed primarily to detect transient sources but will provide data which can also be used for large-scale imaging but with limited sensitivity.

However it is quite clear that the diffuse emission from the Galaxy extends well beyond the GCDE longitude range 330^o- 30^o. The atomic HI extends over the whole plane, and CO (tracing molecular clouds) out to at least 300^o - 60^o. The ^{26}Al extends to Cygnus and Vela, and the EGRET emission follows the gas and so its overall peak extends out to 300^o- 60^o. The diffuse continuum at MeV energies also extends beyond 330^o- 30^o although the sensitivity of COMPTEL was not sufficient to map this in detail. The hard X-ray emission seen by OSSE, RXTE, GINGA, ASCA is also not confined to the inner radian. Gamma-ray sources as discovered by COMPTEL and EGRET are also expected to extend to greater longitudes than covered by the GCDE. Specific time-variable hard X-ray sources falling in the area covered can also be monitored; we consider GRS1915+105 and SGR 1900+14 and various burst sources. Detailed arguments for the various astrophysics goals are given in later sections.

We note that interpretation of large-scale Galactic structure in gamma rays depends very much on detecting angular variations and contrast in the emission on scales of at least 10^o; given only the GCDE coverage this will be quite limited, and will be much enhanced by the proposed extension.

Independent of this, we note that the SPI imaging benefits from an extension in latitude in the GCDE and will also benefit for the proposed extension in longitude; indeed artefacts at the longitude boundaries are visible in SPI simulations (Strong et al. 1999a) and these will be eliminated when combined with the observations proposed.

Therefore the astrophysical interest in extending the GCDE sensitivity to the inner 120^o affects a very wide range of subject areas. In each area the extension will greatly enhance the value of the GCDE itself, and will provide essential information for the interpretation of the inner Galaxy emission. A further extension to greater longitudes could be envisaged in following years with the long-term aim of a deep exposure of the entire Galactic plane.

Data Rights

Data rights are requested for the following topics:

1. Diffuse Galactic continuum radiation, all energies
2. Diffuse Galactic ^{26}Al 1809 keV line
3. Diffuse Galactic ^{60}Fe 1173/1332 keV lines
4. Galactic ^{44}Ti 1157 keV line
5. Unidentified EGRET sources listed in Table 1
6. GRS1915+105
7. SGR 1900+14
8. Burst sources to monitor listed in Table 2.

In each case, JEM-X, SPI and IBIS data are requested. For the point sources, OMC rights are also requested. Data rights for the 511 keV line are claimed in a separate proposal (see below).

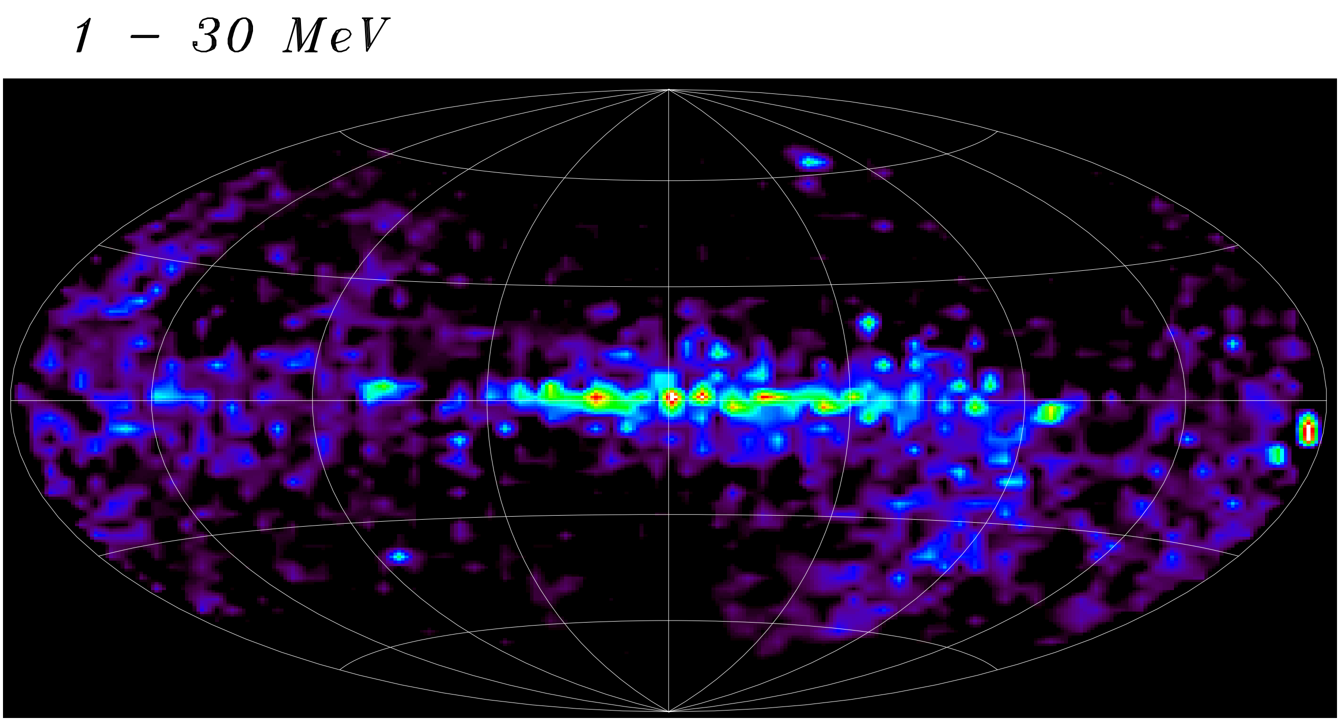
Diffuse Galactic Continuum Radiation

The Galactic diffuse continuum emission has been mapped by COMPTEL at MeV energies (Strong et al. 1999b); it originates partly in interactions of electrons with gas via bremsstrahlung and with intersellar radiation via inverse Compton scattering, but a significant part probably comes from a population of unresolved point sources (e.g. similar to the Crab SNR). Fig 1 shows the COMPTEL map for the 1 - 30 MeV energy range, and Fig 2 shows the spectrum of the inner Galaxy as determined by COMPTEL, EGRET and OSSE. In the COMPTEL map the Galactic disk stands out together with prominent Galactic sources like the Crab, Cyg X-1 and the Vela pulsar. The diffuse emission is concentrated within longitudes 300^{o}- 60^{o} , but is present at a lower level at all longitudes. A detailed mapping of the MeV continuum by INTEGRAL in particular by SPI will allow a better evaluation of the competing processes, and will be considerably enhanced by the proposed extension to l=+/-60^{o} where there is still significant emission.

The emission in 50 - 500 keV has been detected by OSSE (Kinzer et al. 1999) in the inner Galaxy and also around l=95^{o} (Skibo et al. 1997). The spectrum indicates that again a population of point sources is required since diffuse processes seem inadequate. However the OSSE instrument was not capable of resolving point sources in the inner Galaxy, while INTEGRAL will be able to do this. In particular the ability of INTEGRAL to simulataneously measure diffuse emission and point sources will be decisive in separating these components.

The 10- 30 keV hard X-ray emission has been studied using RXTE, GINGA and ASCA (Valinia et al. 2000 and references therein). The emission is intense, but in this case a source population does not seem to be responsible (Tanaka et al. 1999) since the number of low-luminosty sources required violates constaints on known populations. So a diffuse origin from suprathermal electrons or protons has been suggested, although this itself has problems since the power requirements for particle acceleration are very large, and this has significant implications for the energy balance of the Galaxy..

The diffuse continuum emission in the entire energy range accessible to INTEGRAL therefore represents several major unsolved problems in high-energy astrophysics, and INTEGRAL observations can lead to very significant progess by mapping the emission and making an determination of the spectrum with unprecedented accuracy. Especially SPI will be able to make good maps and spectra from 30 - 2000 keV; an example is shown in the simulation in the section on observation details. Measurements of the diffuse emission in the hard X-ray range by IBIS are also expected to be feasible.



Fi g 1. Map of the Galactic plane for 1 - 30 MeV, based on COMPTEL data (Strong et al. 1999b)

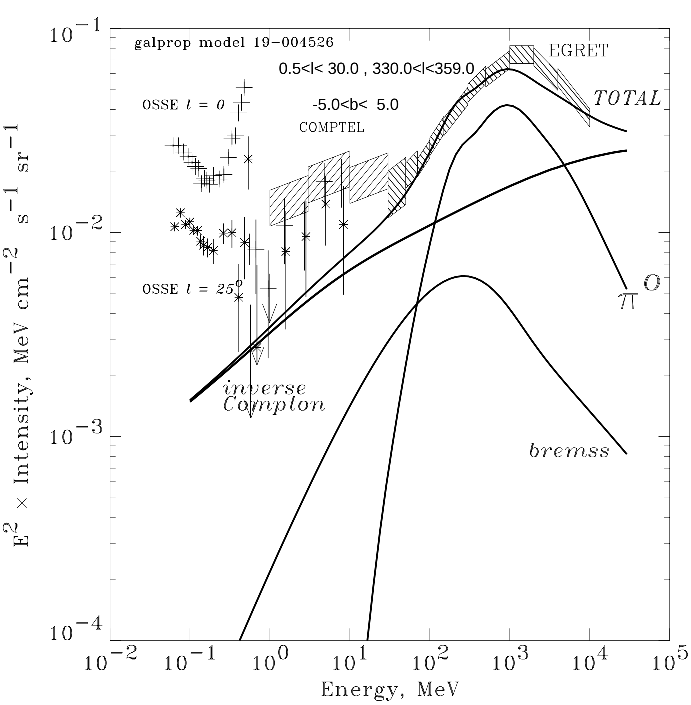


Fig 2. Spectrum of continuum emssion from the inner Galaxy measured by EGRET, COMPTEL and OSSE, together with theoretical predictions for bremsstrahlung, inverse Compton and pion-decay (Strong et al. 2000),

Galactic diffuse 1809 keV line of ^{26}Al and 1173/1332 keV lines of ^{60}Fe

Astrophysical interpretations of ^{26}Al observations aim at the determination of the massive star content (for the amount of ^{26}Al in a particular region of the Galaxy, reflected in the measured 1.809 MeV gamma-ray line flux) and the conditions of the interstellar medium in this region (reflected in the measured gamma-ray line shape). Both measurements translate into an assessment of the formation and evolution of massive stars in the Galaxy (Diehl and Timmes 1998).

These processes depend rather strongly on environmental parameters of the region, the expected spatial variations of ^{26}Al production and line shape therefore are an important scientific objective. Regions with more recent massive star nucleosynthesis should display a broader line, as an average trend; this may not be significant for individual regions due to the spread in ISM turbulence and due to specific momentary states of a region; analysis of a larger sample of massive star regions is required, and more exposure of directions outside the distance-confused inner-Galaxy lines-of-sight are proposed here. As a derivative, the ^{60}Fe radioactive isotope is co-produced by some, but not all of the ^{26}Al source types: core-collapse supernovae are expected to produce both isotopes, while massive stars such as Wolf-Rayet stars are probably the dominating sources of ^{26}Al, and less massive stars such as AGB stars probably are significant sources of ^{60}Fe (but not of ^{26}Al). The spatial distribution of these different mass ranges of massive stars should be different because of the mass/lifetime ratio, most massive stars shedding their nucleosynthesis products closer to their formation sites. Since ^{60}Fe cannot easily be detected through purely spectral measurement of the gamma-ray line signal, but requires spatial information, we propose to broaden the basis for ^{60}Fe search with this extended survey, which will allow us to add significant imaging information to aid the search for Galactic ^{60}Fe nucleosynthesis. The study of massive stars in conventional (optical) spectral windows is hampered by Galactic extinction, hence has been performed mainly in nearby regions of the Galaxy (and extragalactic regions). Gamma-rays from ^{26}Al and ^{60}Fe reach us from everywhere in the Galaxy, hence allow a complete survey of the massive-star activity in the Galaxy.

The INTEGRAL core program will focus on the inner part of the Galaxy and will provide the key data for the Galactic ^{26}Al production and its typical conditions, because towards the inner Galaxy the line of sight integrates over production regions within several kpc distance. For the study of spatial variations, however, it is essential to be able to compare these integrated ^{26}Al results to results obtained from directions where more specific source locations can be assumed. Due to the above-mentioned optical extinction limitations, most, if not all, such source location assignments carry substantial uncertainty; such uncertainty is reduced in derived results for massive-star regions if we can analyze a variety of cases. Therefore we propose to extend the ^{26}Al survey over a larger part of the plane of the Galaxy, specifically including less confused directions. Note that the ^{26}Al emission appears with a strong spatial gradient outside of longitudes +/- 35^{o} (Diehl et al. 1995; Plüschke et al. 2001) ; our proposed extension of the survey to the area between +/-30^{o} and +/-60^{o} longitude emphasizes these directions, where apparently there is a major change compared to the inner Galaxy in either the massive-star population or their environmental conditions. We suspect that tangential directions towards spiral arms are the main reasons for these sharp drops in ^{26}Al emission. This will allow us to analyze changes in ^{26}Al emission characteristics on these unique lines of sight, and enable their comparison to inner-Galaxy results. Similarly, for the search for ^{60}Fe it will be advantageous to be able to test different spatial-distribution models in the spectral bands of the ^{60}Fe gamma-ray lines at 1.332 and 1.173 MeV; such hypothesis testing addresses the astrophysical issues of the ^{60}Fe source types directly, and significantly improves the sensitivity over a ^{60}Fe line search without adding prior knowledge. The spatial distributions of very massive stars and AGB stars should best be discriminated at spiral-arm trailing edges: within spiral arms the overall signal is expected to be largest, and its trailing shape should encode the average mass of the source stars.

A simulation of the ^{26}Al map based on combined GCDE and extension is shown in Fig 5 (see Observation Requirements section).

^{44}Ti line source survey

The frequency of supernovae in the Galaxy is still not accurately known: historical records are strongly affected by extinction, and remnant surveys also suffer from source confusion; even indirect measurements from Hα emission or other secondary and more global effects are difficult from our position within the Galactic disk. The possibility of detecting radioactivity in the 1157 keV gamma-ray line of ^{44}Ti decay presents a unique alternative: with a decay life-time of 89 years, the ^{44}Ti afterglow duration is sufficient for a sampling time of several centuries, yet small enough to yield a sufficiently-intense signal without diffusing it over too many sources with admixture of non-supernova contributions (as is the case for the ^{26}Al afterglow). The penetration of gamma-rays ensures that such supernova rate measurements are unaffected by extinction. The main uncertainty lies in the supernova mechanism, through the uncertain ejection of material close to the mass cut (see Diehl and Timmes 1998 for a review).
The detection of ^{44}Ti gamma-ray line emission from the 330 year old Cas A supernova remnant has demonstrated the validity of this approach (Iyudin et al. 1994). The analysis of the ^{44}Ti record of past supernovae should use a gamma-ray survey which covers the relevant signal area (e.g. Diehl 2001); this is best given by the locations of recent massive star formation as reflected in the COMPTEL ^{26}Al map along the Galactic plane (Diehl et al. 1995; Plüschke et al. 2001). Relative to the historical record of optical supernovae, a detailed simulation study based on the COMPTEL inner-Galaxy survey part was able to demonstrate the capability for supernova recurrence rate determination (The et al 2000), accounting for all uncertainties even including the ^{44}Ti issues. It is important to use a spatially extended survey as baseline for such studies, in particular since the present hints for ^{44}Ti sources from COMPTEL appear to not be concentrated in the inner Galaxy, so we emphasize the need for extension of the INTEGRAL survey also for this study.

EGRET Unidentified Point sources

The 3rd EGRET catalog (Hartmann et al. 1999) contains 17 unidentified sources (>100 MeV) in the range l = 300^{o}-330^{o} and l = 30^{o}- 60^{o} , $|b|<20^{o}$. These are sources whose nature is quite open and the subject of considerable attention (e.g. Kaaret 1998). We note that this longitude range is less source-confused than the inner 60^{o}, which should assist in unambiguous identification. Detections of these sources by IBIS, SPI and in particular JEM-X would improve enormously their positional accuracy and enable follow-up identifications at other wavelengths. The spectral information in conjunction with the EGRET spectra will help to reveal their true nature (SNR, pulsars, a new class ?).

Table 1: EGRET unidentified sources in survey area

ID	RA	dec	l	b
3EG J1300-4406	195.06	-44.10	304.60	18.74
3EG J1308-6112	197.18	-61.22	305.01	1.59
3EG J1316-5244	199.24	-52.75	306.85	9.93
3EG J1410-6147	212.73	-61.73	312.18	-0.35
3EG J1420-6038	215.11	-60.64	313.63	0.37
3EG J1447-3936	221.95	-39.61	326.12	17.96
3EG J1659-6251	254.97	-62.86	327.32	-12.47
3EG J1813-6419	273.34	-64.33	330.04	-20.32
3EG J1822+1641	275.57	16.70	44.84	13.84
3EG J1825+2854	276.29	28.91	56.79	18.03
3EG J1828+0142	277.25	1.72	31.90	5.78
3EG J1856+0114	284.10	1.24	34.60	-0.54
3EG J1903+0550	285.91	5.84	39.52	-0.05
3EG J1928+1733	292.10	17.56	52.71	0.07
3EG J1940-0121	295.23	-1.36	37.41	-11.62
3EG J2036+1132	309.18	11.54	56.12	-17.18
3EG J2046+0933	311.58	9.57	55.75	-20.23

GRS 1915+105

This peculiar source has been the subject of intense study since its discovery in 1992 (Castro-Tirado et al., 1992,1994). It was the first Galactic source for which superluminal motion of transient radio lobes was detected (Rodriguez & Mirabel, 1994). The source exhibits extreme variability in the time structure of its X-ray emission and a whole classification scheme has been developed for just this source (Belloni et al., 2000). Observations of 67 Hz QPO signals from GRS 1915 have been used to support the suggestion that this source harbours a high mass (10 M_{Sun}) stellar black hole (Cui et al., 1997). We are aware that several open- time proposals and Core Programme studies on GRS 1915+105 are in preparation including target of opportunity observations.

The additional time coverage of this source (at l = 45.37^o, b = - 0.22^o) provided by our proposed survey (4 x approximately 15 hours) can in themselves provide data on source variability and of the persistence of any hard tail emission out about 300 keV and will provide an improved database for the possible selection of TOO time intervals.

SGR 1900+14

The Soft Gamma-ray Repeater 1900+14 (hereafter SGR 1900+14) was first detected by the Konus experiment on VENERA 11 and 12 on 24-27 March 1979, when it produced three outbursts (Mazets et al. 1979), coming from the same direction of the sky, centered at l = 43.80^o, b = +1.60^o. Thirteen years later, a series of events detected by BATSE on CGRO was tentatively attributed to SGR 1900+14 (Kouveliotou et al. 1993), suggesting that SGRs can become active again after many years. An improved position was obtained by Hurley et al. (1994) by combining the data from the Ulysses gamma-ray burst detector and BATSE. Very close to this tiny error box, an X-ray source was found with the ROSAT HRI detector (Hurley et al. 1995). This was tentatively suggested as the long sought X-ray counterpart to SGR 1900+14, just outside the galacitc SNR G42.8+0.6. The X-ray source has a quiescent luminosity of 3 10^{34} erg/s (2-10 keV). In 1998, SGR 1900+14 entered a new prolific period, the third one since 1979, undergoing a giant flare on 27 Aug 1998, probably the most intense burst ever recorded at Earth (Hurley et al. 1999), reaching a luminosity of 2 10^{43} erg/s (> 25 keV). A search for a transient IR counterpart was unsuccesful (Castro-Tirado et al. 2000). Now SGR 1900+14 is well established as X-ray pulsar with a rotation period of 5.16s and spin down of period derivative ~ 10^{-10} s s^{-1} suggesting a magnetar origin: a neutron star with a magnetic field of B ~ 10^{15} G (Kouveliotou et al. 1999). Only four such SGR sources are known in our Galaxy. The additional time coverage of the quiescent counterpart provided by our proposed survey will provide an important data base for the possible selection of TOO time intervals.

Nuclear synthesis signatures from X-ray bursts

We propose to combine data from a number of X-ray bursts observed serendipitously in pointed INTEGRAL observations to search for emission above 100 keV related to X-ray bursts. This proposal primarily concerns emission which arises from short-lived nuclear species created during the burst. We would like to have access to data from all four INTEGRAL instruments for all periods within the extended survey where any of the objects listed in Table 2 is visible, in order to be able establish the accretion state (M-dot, spectral hardness, QPO activity) of the sources prior to the bursts.

Only a small fraction of the freshly synthesized material may appear at the surface of the neutron star or be expelled during the flash. We have estimated that the flux of nuclear gamma rays emitted from the burster surface may bebetween 10^{-4} and 10^{-5} of the flux of X-ray photons (2-10 keV). Therefore we only expect one or a few gamma photons per burst, and we will need to combine many bursts to obtain a significant result. We intend to propose a similar investigation within the Core Programme to extend our data base. We will use the data to estimate the importance of convection and mixing of the upper layers of the neutron star during an outburst and possible ejection of matter from the star. We will also search for spectral features (lines) and attempt to identify signatures of specific reaction chains.

We realize that current models of unstable nuclear burning does not predict a measurable flux of nuclear gamma rays. However, INTEGRAL carries the most sensitive instrumentation build to date for the detection of such emissions. If detected nuclear gamma rays could provide many important constraints for the theory of nuclear burning on the surface of compact objects.

Table 2: X-ray burst sources in the galactic longitude intervals covered by the proposed survey extensions.

ID	RA	dec
4U 1254-690	12 57 37.20	-69 17 21.0
4U 1323-619	13 26 36.10	-62 08 10.0
MXB 1422-62	14 26 00.00	-62 00 00.0
Cen X-4	14 58 22.00	-31 40 08.0
Cir X-1	15 20 40.90	-57 10 01.0
4U1608-52	16 12 43.00	-52 25 23.0
4U1636-53	16 40 55.50	-53 45 05.0
Ser X-1	18 39 57.50	05 02 09.0
MXB 1906+00	19 08 27.00	00 10 08.0
Aql X-1	19 11 16.00	00 35 06.0
4U 1915-05	19 18 48.00	-05 14 09.0
Ha 1940-04	19 42 38	-03 53

Observation Requirements

The GPS covers the latitude range $|b|< 6.5^o$, compared to the GCDE principal range of $|b|<10^o$ with extension to $|b|= 20^o$ with 1/4 of the exposure. The exposure to $|b| <10^o$ is therefore $3.2\ 10^6$ sec. The GPS therefore is equivalent in terms of exposure per year to

$(2.3\ 10^6/3.2\ 10^6) \times (60^o/360^o) \times (10^o/6.5^o) = 0.18$ GCDE equivalents $= 0.6\ 10^6$ sec GCDE

Since the GPS also covers the longitude range required, we require

$$(3.2 - 0.6)\ 10^6 \text{ sec} = 2.6\ 10^6 \text{ sec}$$

of exposure in the longitude ranges 300^o- 330^o and 30^o- 60^o.

The proposed observing strategy is to make 12 5X5 standard dithering patterns of 2^o pitch to cover the 1200 square degrees, giving 300 pointing each pointing having 1800s giving $5.4\ 10^5$ s.This is to be repeated 4 times to give a total of $2.16\ 10^6$ s. A shift of 1^o between repeated patterns will improve the sampling of the detector planes for all instruments. An additional 12 5X5 ditherhing patterns for the same longitudes but for $10^o<|b|<20^o$, performed only once, to reduce SPI artefacts, brings the total up to $2.7\ 10^6$ s.

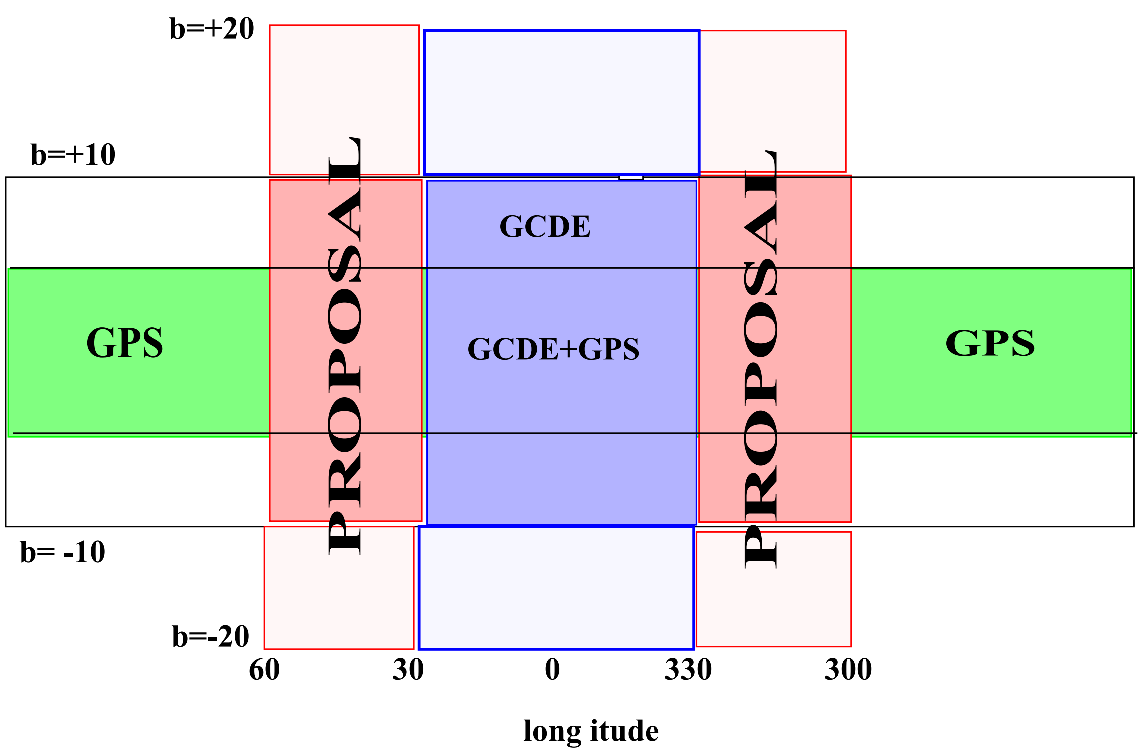


Fig 3. Sketch of coverage of proposed observations, marked PROPOSAL.
Light shading indicates lower exposure.
For comparison the GCDE and GPS are also shown.

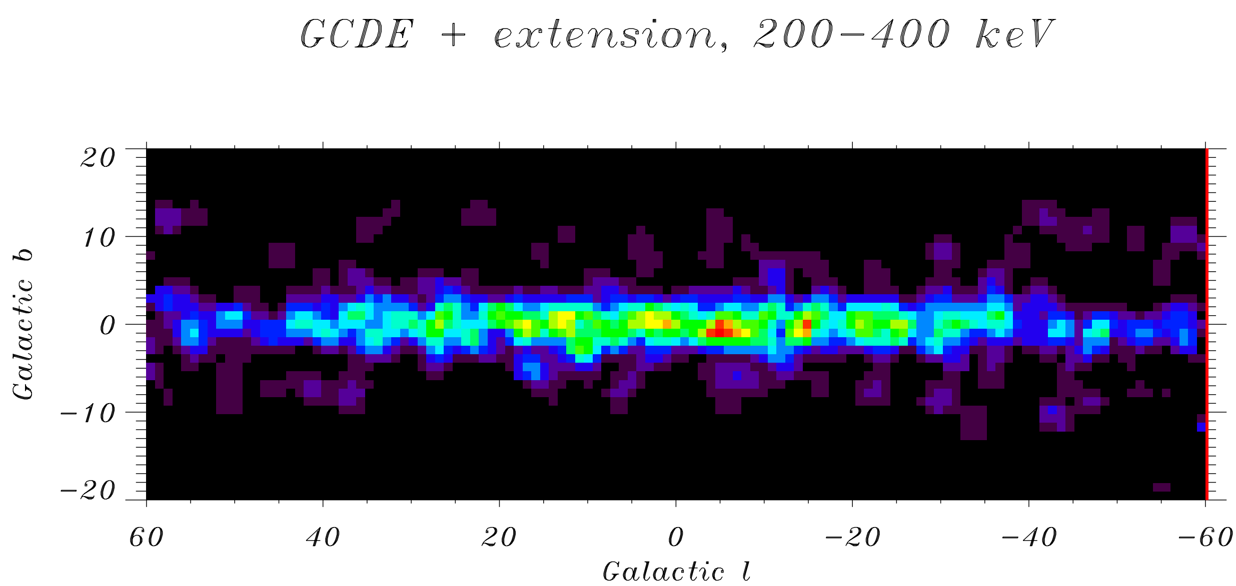


Fig 4: Simulation of 200-400 keV diffuse continuum emission imaging using core GCDE + the proposed extension.

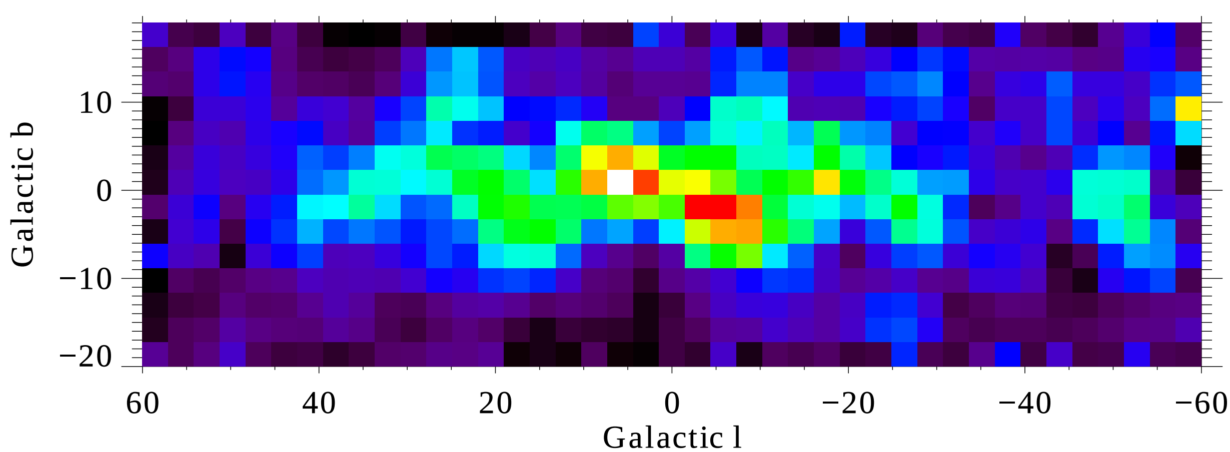


Fig 5: Simulation of ^{26}Al imaging based on the COMPTEL map and core GCDE + the proposed extension.

A simulated image of the diffuse continuum in 200-400 keV using the GCDE plus the proposed extension is shown in Fig 4. This was produced with the ISDC SPI Observation Simulator (Strong 2000). It shows that the emission is well imaged out to l = +/-60^o . A simulation of the same observations for the ^{26}Al line, based on the COMPTEL map, is shown in Fig 5. Again the advantage of the extension to the emission beyond l=+/-30^o is clearly visible .

The requested observations can in part be made in parallel with other proposals covering the same area, thus reducing the exclusive time for this proposal. ISOC is invited to consider combinations to optimize such parallel use of time. In this respect we note that the pointing directions requested are flexible up to a few degrees, which will ease the assignment of such cases.
We also propose for Data Rights for the present science topics to any AO1 observations of this area which do not include these topics. Since there are likely to be a significant number of these this will significantly improve the exposure without requiring extra time from the Open Time.

Parallel Proposal.

A parallel AO-1 proposal "*511 keV annihilation radiation from the GCDE longitude extension*" has been submitted by Skinner et al. ,Proposal ID:0120021, (with some co-Is in common with the present proposal, but with a team interested in particular in positron production and annihilation). The objective of the related proposal is to study the line shape and centroid energy the 511 keV radiation and to investigate its distribution beyond the central radian. Like this one, the proposal is to make exposures in the shoulder region, $l=30^o$ to 60^o and $l=300^o$ to 330^o. For that proposal the same sequence of exposures as proposed here is to be used, but the data will be analysed from the point of view of the 511 keV annihilation radiation line. Thus the two proposals are designed so that a single pointing sequence can achieve two objectives.

Data analysis and combination with GCDE.

The team of CoIs includes instrument expertise for SPI, IBIS and JEM-X, having the data-analysis software and competence to analyse the data effectively. Since the Instrument CoIs will also have access to the GCDE from the Core Program, the data will be combined with the GCDE, as is required for an optimum analysis. It is proposed to make this combination as part of the ISWT's GCDE analysis.

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