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Infrared observations of soft gamma repeaters

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Abstract. We have made IRAS (12, 25, and 60 μm) maximum entropy images of the three known soft gamma repeaters SGR 0526–66, SGR 1806–20, and SGR 1900+14. In addition we have obtained a high-resolution 10 μm image of SGR 1900+14 using TIMMI at the ESO 3.6 m telescope. All three SGRs have associated with them an infrared source. The infrared emission associated with SGR 0526–66 likely originates from heated dust in the supernova remnant N49. The infrared properties of the two galactic SGRs are similar; both are unresolved at 12 and 25 μm, and extended at 60 μm. The relation of these infrared sources (if any) to the SGRs is as yet unclear.

Key words: gamma rays: bursts – circumstellar matter – supernova remnants – infrared: ISM: continuum

1. Introduction

Soft Gamma Repeaters (SGRs) are sources of brief intense outbursts of low-energy gamma radiation. They differ from the "classical" gamma-ray bursts (GRBs) with respect to several basic properties. (i) As their name indicates, the SGR events repeat; there is no convincing case known of repetitive GRBs from a single source (Briggs et al. 1995). (ii) At energies above their spectral peaks the spectra of these events are well described by optically thin thermal bremsstrahlung with kT $\sim$ 30 keV (Fenimore et al. (1994); thus they are much softer than those of the vast majority of GRBs (Kouveliotou 1994), whose emissions peak at several hundreds of keV, and some of which have been detected all the way to the tens of GeV range (Hurley et al. 1994a). (iii) SGR events tend to be very brief, with a typical duration of 100 milliseconds, as compared with an average duration of roughly 10 seconds of GRBs (Kouveliotou et al. 1993).

The combined spectral and temporal characteristics of SGR events are sufficiently uniform, and different from those of GRBs, that it is warranted to consider them a single class of events (see Norris et al. 1991). Three SGRs are known so far, all discovered between 1979 and 1983; based on their rudimentary sky distribution, Kouveliotou et al. (1987) suggested that SGRs are a young galactic population.

Recently, progress has been made in our knowledge of SGRs by detections of counterparts in other parts of the electromagnetic spectrum. For SGR 0526–66, long known to be located at the edge of the supernova remnant N49 in the Large Magellanic Cloud (Cline et al. 1982; see Vancura et al. 1992, for a detailed study of this SNR), a soft X-ray counterpart (a 'hot spot' in N49) was recently found with ROSAT (Rothschild et al. 1994). So far, this object does not have an optical or radio point source counterpart (Dickel et al. 1995).

Kulkarni & Frail (1993) pointed out that also the error box of SGR 1806–20 contains a catalogued supernova remnant, G10.0-0.3, and suggested that a compact radio source inside this SNR may be a plerionic component related to a young pulsar. This suggestion was soon followed by a new period of SGR activity of this source detected with BATSE (Kouveliotou et al. 1994), the first in a decade. Rapid follow-up observations were made with ASCA, in which a steady X-ray source and a burst was detected simultaneously with BATSE (Kouveliotou et al. 1994; Murakami et al. 1994; see also Cooke 1994). The imaging capability of ASCA allowed the burst source to be located to arcminute accuracy. Its position coincides with that of the steady X-ray source, which in turn coincides with the com-

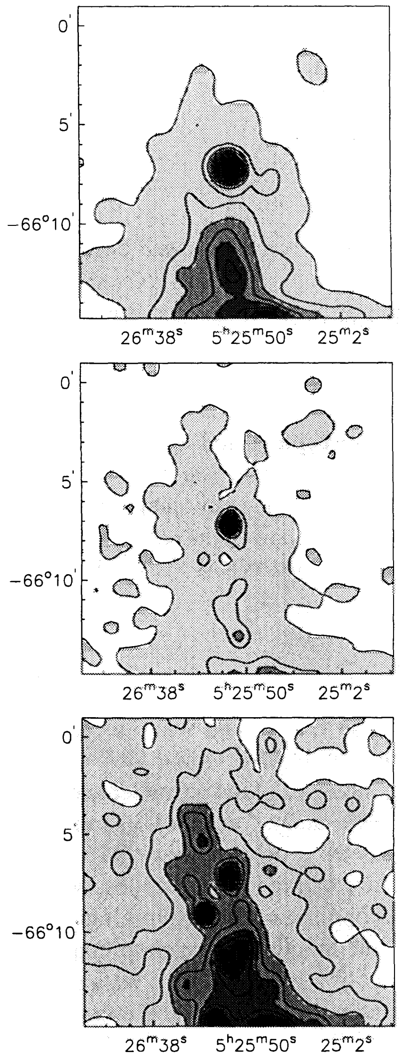

Fig. 1. HIRAS maximum entropy images of SGR 0526–66 at 60 μm (top), 25 μm (center), and 12 μm (bottom). The center of the image is at RA (1950) = 05:25:56, DEC (1950) = –66:07:03. The contours indicate levels (in units of MJy per steradian) from 0.5 to 5, in steps of 0.5 (for 12 μm), from 1 to 28 in steps of 3 (for 25 μm), and from 10 to 100 in steps of 10 (for 60 μm).

pact radio source in G10.0-0.3 singled out by Kulkarni & Frail (1993). A highly reddened star, located within an arcsecond of this radio source, was suggested as the counterpart (Kulkarni et al. 1995; Vasisht, Frail & Kulkarni 1995). Near-infrared spectroscopy (Van Kerkwijk et al. 1995) showed that this star is likely a Luminous Blue Variable (LBV), a rare type of very luminous massive star, reddened by $A_V \sim 30$ magnitudes.

The error box of the third SGR, 1900+14, has recently undergone an enormous improvement in accuracy, due to the application of the so-called network synthesis method (Hurley et al. 1994c). Scanning of a grid of positions near the known error box of SGR 1900+14 has resulted in two possible positions, with error boxes of $\sim$ 3 by 10 arcminutes. One of these is located very close to a known SNR, G42.8+0.6, which was tentatively identified with a soft X-ray source by Vasisht et al. (1994). ROSAT

Table 1. IRAS flux densities (in Janskys)

SGR	12 μm	25 μm	60 μm
0526–66	0.28 ± 0.05	1.75 ± 0.20	13.0 ± 2.0
1806–20	0.98 ± 0.05	35 ± 3	29 ± 5
1900+14	2.5 ± 0.2	6.3 ± 0.3	12.3 ± 1.5

observations of the latter error box led to the detection of 11 X-ray sources, by far the brightest of which is consistent with the source reported by Vasisht et al. (Hurley et al. 1995). Optical and infrared observations show that very near this ROSAT source is a pair of heavily reddened IR bright objects, separated by $\sim$ 3 arcseconds. These two components have strikingly similar optical spectra, and they may be stellar, with spectral types approximately M3 for both of them (Hartmann et al. 1995; Vrba et al. 1995). The IR and X-ray emissions coincide, suggesting a connection between SGR 1900+14 and the IR/X-ray source; however, we caution that the sources are located slightly outside the network synthesis error box.

The association of SGRs with young SNR would suggest that SGRs are a phenomenon connected with a short-lived phase in the lives of at least some young neutron stars, consistent with the idea that they are relatively rare sources (Kouveliotou et al. 1994; Hurley et al. 1994b). Distance estimates based on these associations indicate that the peak luminosity reached during the SGR events ranges between 10^{40} and 10^{42} erg/s, far above the Eddington luminosity of a neutron star (the first event detected from SGR 0526–66, the famous March 5, 1979 event, reached a peak luminosity of 10^{44} erg/s). The energy source of these events is yet unknown. The SGR events may therefore be a completely new manifestation of neutron stars, or perhaps even black holes.

What causes SGRs to be different from other young neutron stars is not known; high velocities (Kulkarni et al. 1994) and very strong magnetic fields (Thompson & Duncan 1995) have been suggested, but how these fit the suggested connection with stellar counterparts is unclear.

Clearly, detailed knowledge of the emission of SGRs over as wide a spectral range as possible is important, and may provide guidance and constraints to modelling of these objects. We here report photometric measurements in the infrared, based on the IRAS data base, and on 10 μm observations at ESO, and discuss their implications (see also Smith et al. 1995).

2. Observations and data analysis

2.1. IRAS observations

The IRAS data were analysed using HIRAS, a maximum entropy image restoration technique designed to deal with the peculiar way the observations were taken (see Bontekoe et al. 1994). HIRAS runs within the GIPSY software package (Van der Hulst et al. 1992). The spatial resolution of the HIRAS images depends somewhat on the S/N and may vary throughout the image, but can approach the diffraction limit of the telescope, which is about 1 (1.7) arcmin at 60 (100) μm. HIRAS images of point sources give FWHM of 39 ± 2 arcsec at 12, 25

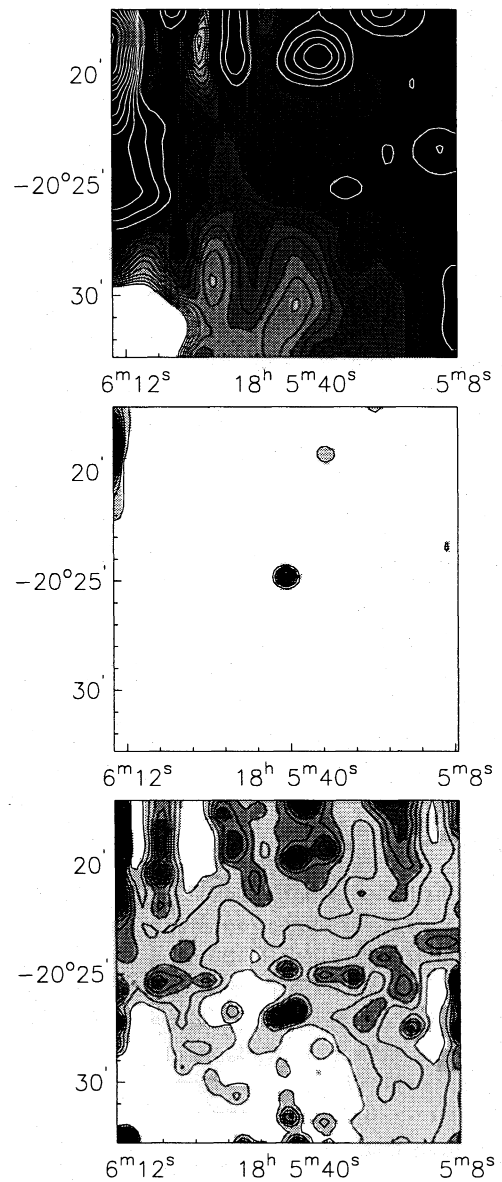

Fig. 2. HIRAS maximum entropy images of SGR 1806–20 at 60 μm (top), 25 μm (center), and 12 μm (bottom). The center of the image is at RA (1950) = 18:05:41.8, DEC (1950) = –20:25:13. The contours indicate levels (in units of MJy per steradian) from 5 to 50, in steps of 5 (for 12 μm), from 100 to 1000 in steps of 100 (for 25 μm), and from 2^5 to $2^{8.5}$ in (logarithmic) steps of 0.25 (60 μm, black contours), and from $2^{8.5}$ to 2^{15} in (logarithmic) steps of 0.5 (60 μm, white contours).

and 60 μm (Izumiura et al. 1996), and 80 ± 10 at 100 μm. We show the resulting images at 12, 25, and 60 μm in Figs. 1 to 3. No reliable images could be constructed at 100 μm due to the strong background at this wavelength.

The infrared flux densities were obtained by surface photometry of the HIRAS images. Since all sources lie in areas with a bright and complex background, the resulting flux densities depend on the detailed shape of the background. This introduces some uncertainty in the results. The dominant source of error in the flux density determination is the choice of aperture, since in some cases the distinction between source and background could not easily be made (especially at 60 μm). The resulting flux densities are given in Table 1. Note that the values for all three SGRs agree reasonably well with those given in the IRAS Point Source Catalogue (IRAS Science Team 1985).

Table 2. Source extensions (FWHM of 2-D fits, in arcsec)

SGR	12 μm	25 μm	60 μm
0526–66	69 × 52	54 × 44	72 × 68
1806–20	58 × 39	38 × 38	196 × 131
1900+14	37 × 35	39 × 39	96 × 67

For all three infrared sources the position is within 30 arcsec of the known SGR position (see captions to Figs. 1 to 3), which suggests that the IRAS and soft-gamma sources are related. The images show evidence for extended emission at 60 μm in all three cases. We fitted 2-D Gaussians to the central source in all images; the resulting values of the FWHM are listed in Table 2.

2.2. *TIMMI observations*

We observed SGR 1900+14 in the N band with the Thermal Infrared Multi-Mode Instrument TIMMI (Käufl 1994), an infrared camera at the Cassegrain focus of the 3.6 meter telescope at the European Southern Observatory, from UT 07:11 to 07:33 on June 11th, 1995. We selected a field of view of 25 arcsec with a corresponding pixel size of 0.4 arcsec. The observations were made in a standard chopping mode, with a chop throw of 9 arcsec in the North-South direction, and a chop frequency of 5.4 Hz; to avoid the effect of a gradient in the background, source and background location were exchanged every ~ 90 seconds. The image clearly shows the pair of stellar objects reported by Hartmann et al. (1995). The instrumental magnitudes were determined using simple aperture photometry software. We used the photometric calibration of the N band of Van der Bliek et al. (1995). From a comparison with the results of the standard stars α Cen A and λ Vel we find N band flux densities of 1.64 and 0.86 Jy for the Eastern and Western components of the pair, respectively. We estimate these values to be accurate to better than 5 percent. The pair of M stars is surrounded by faint extended emission (see Fig. 4). Because the extent of this emission is comparable to the chop throw it is not possible to measure the flux density of this component.

2.3. *IRTF observations*

On July 29, 1995 we used the NASA Infrared Telescope Facility (IRTF) to observe SGR 1900+14, using the Facility bolometer with a 6 arcsec-diameter (FWHM) aperture. Offsetting from the nearby star SAO 124308, the aperture was centered at RA = 19:04:52.0, Dec = +09:14:35 (1950). The measurements were made at 10.2 and 20 μm with exposure times of 800 and 1000 s, respectively. We measured flux densities of 1.52 ± 0.06 Jy and 1.79 ± 0.26 Jy at 10.2 and 20 μm, respectively. During these measurements neither of the two stars was centered on the aper-

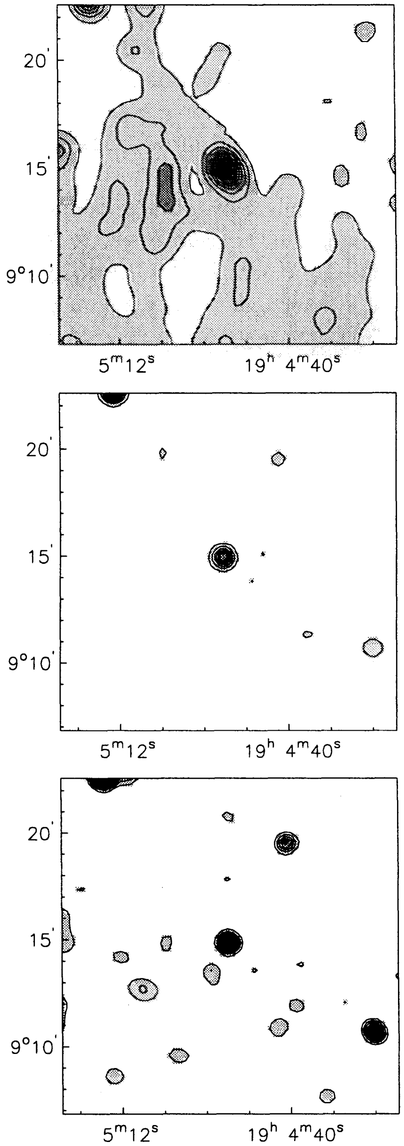

Fig. 3. HIRAS maximum entropy images of SGR 1900+14 at 60 μm (top), 25 μm (center), and 12 μm (bottom). The center of the image is at RA (1950) = 19:04:52.0, DEC (1950) = +09:14:35.1. The contours indicate levels (in units of MJy per steradian) from 5 to 50, in steps of 5 (for 12 μm), from 10 to 250 in steps of 20 (for 25 μm), and from 10 to 100 in steps of 10 (for 60 μm).

ture; relative to the center of the aperture the stars were located at (+2, +1.8) and (-1.4, +1.2) in units of arcseconds. Thus, we would expect the flux from each star to be down by about a factor of two relative to the TIMMI observations, which is consistent with the observations. Despite the non- optimum position in the bolometer aperture, these observations both confirm the detection of these sources at 10 μm and extend them to 20 μm; they show that the spectrum of the pair in the 10 to 20 μm range is nearly flat.

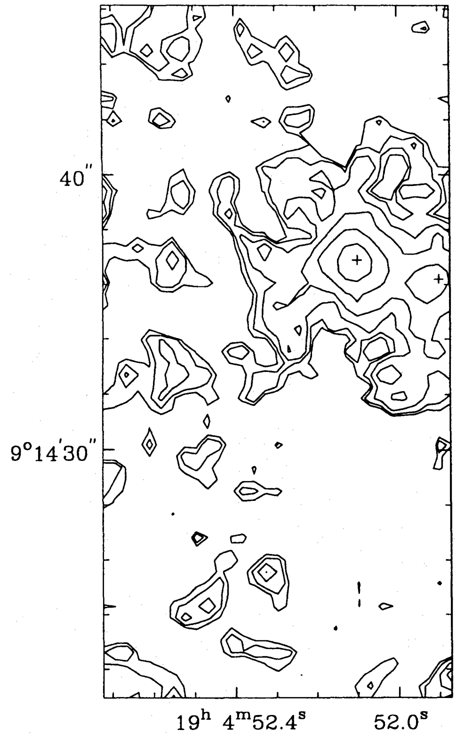

Fig. 4. Contour plot of the TIMMI image of SGR 1900+14, showing the presence of extended emission around the pair of M-type stars. The contour levels correspond to 28, 56, 112, 224, 448 and 896 mJy per square arcsec.

3. Results

3.1. *SGR 0526–66*

Inspection of individual IRAS scans as well as the HIRAS images suggests that the IR emission of SGR 0526–66 is extended (see also Table 2). At 60 μm the object is roughly round and about 1 arcmin in size. This size agrees very well with the size of the X-ray image published by Graham et al. (1987) of the SNR N49. Graham et al. (1987) concluded that the IRAS colours of N49 can be understood as a result of emission by dust grains, swept up by the supernova remnant, which are heated by hot plasma in the remnant. At 12 and 25 μm the source is somewhat more compact than at 60 μm. This could be due to the fact that hotter dust may be present near the centre of the nebula, or due to forbidden line emission from the highly ionised gas dominating the emission at the shorter wavelengths. Infrared spectroscopy would allow a distinction between both possibilities. We conclude that it is likely that the IR emission from SGR 0526–66 is associated with dust in the SNR and has no direct bearing on the presence of a soft gamma repeater.

To make a more general comparison between the IR properties of the soft gamma repeaters and those of supernova remnants we have, in Fig. 5, plotted their values of log $(F_{12\mu}/F_{25\mu})$ versus log $(F_{25\mu}/F_{60\mu})$, together with those of of galactic supernova remnants in the IRAS survey of Saken et al. (1992), and several luminous blue variables (IRAS Science Team 1985). In

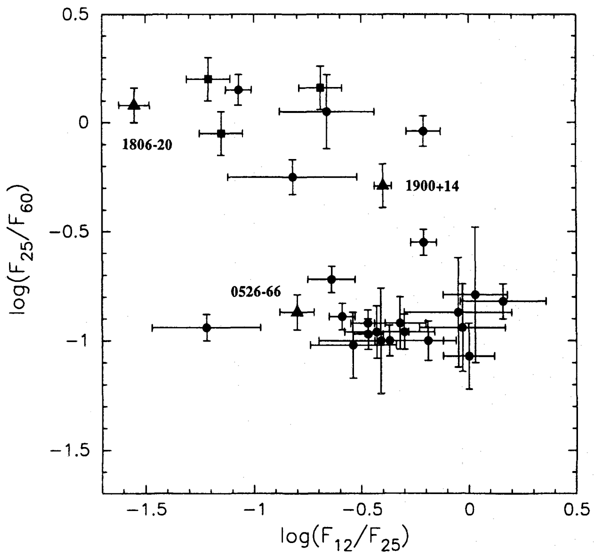

Fig. 5. IRAS colour-colour of the three soft gamma repeaters (indicated by triangles), supernova remnants (indicated by dots; data from Saken et al. 1992), and luminous blue variables (indicated by squares).

this diagram SGR 0526–66/N49 is located close to the region where the galactic SNR are concentrated. This result supports, and puts into a broader context, the above conclusion regarding SGR 0526–66.

3.2. *SGR 1806–20*

The HIRAS images show a point-like source at 12 and 25 μm, and an extended source at 60 μm (Table 2). The colours of SGR 1806–20 are quite different from those of SGR 0526–66 and resemble more those of dusty detached shells around mass-losing stars. The discovery by Van Kerkwijk et al. (1995) of a reddened hot star with a strong stellar wind at the same position suggests that the IRAS source indeed is associated with it. Very massive supergiants or Luminous Blue Variables (LBV's) are known to pass through phases of violent eruptions, resulting in detached dust shells with masses of several $M_\odot$. The IRAS colours of SGR 1806–20 resemble those of some LBV's with dust shells (Fig. 4). The extended emission at 60 μm is somewhat difficult to explain in such a scenario, since one would expect the size of the shell to be roughly similar at 12, 25 and 60 μm (see e.g. Waters et al. 1995). The very high extinction (A_V = 30, Van Kerkwijk et al. 1995) towards SGR 1806–20 may affect the 12μm flux density; however, this does not change our conclusions.

It is conceivable that the 60 μm extended emission is the result of heating of material ejected by the LBV during a previous phase of mass loss. However, at a distance of about 15 kpc (Corbel et al. 1996) the size of the 60 μm source is about 15 pc, substantially larger than dust shells around other LBVs (Humphreys and Davidson 1994); the extended 60 μm emission may originate from heating of ambient interstellar material.

The question whether the extended 60 μm emission is due to heating of dust by high-energy emission from the SGR is difficult to answer. Absorption of high-energy X rays by dust grains is very inefficient, and it seems unlikely that the observed IR source can be accounted for by this mechanism. The situation would be better if a strong EUVE/UV source were present, but the high interstellar extinction does not allow a meaningful statement on this.

Could the 60 μm emission be caused by heating of the same material which causes the 30 magnitudes visual extinction? For typical dust properties one has $A_V = 5.9\ 10^{-11}\ n\ s$, where n is the dust particle density, and s the length of the medium along the line of sight (Trams 1991). For a typical molecular cloud we have a density of 10^4 atoms cm^{-3}, a dust particle density of 10^{-8} cm^{-3} and a gas/dust ratio of 100. To get 30 magnitudes of extinction the required path length is 15 pc, in reasonable agreement with the estimated size of the 60 μm emitter. If, based on the observed IRAS colours, we assume a dust temperature of 30 K for the extended component (the compact IR emitter is hotter), and assume that a volume with radius 15 pc is filled with dust grains at the above given density, the 60 μm flux density of this cloud (distance 15 kpc) would be 1.9 10^4 Jy. This is so much larger than the observed value, that we conclude that there is significant additional foreground extinction.

3.3. *SGR 1900+14*

The IRAS source at the position of SGR 1900+14 is point-like at 12 and 25 μm but clearly extended at 60 μm. We verified whether the elongation at 60 μm could be related to artefacts in the removal of scan effects in the image reconstruction algorithm, but the scan angles in the data covering the position of SGR 1900+14 do not coincide with the position angle of the extended emission. We conclude that the morphology of SGR 1900+14 at 60 μm is real. The IRAS source is not associated with the faint SNR G42.8+0.6, which is located about 30 arcmin south and is very extended (Vashist et al. 1994). It is not clear at present if there is a relation between the IRAS source and the soft gamma repeater.

From the TIMMI observations we find for the sum of the N band flux densities of the two components of the close pair of (likely) stellar objects a value of 2.5 Jy, consistent with the observed IRAS flux density at 12 μm (after allowing for the slightly different wavelengths using the observed IRAS colours). This indicates that, unless the IR flux densities of the two components of the pair are variable on a time scale of years, the IRAS 12μm flux density can be accounted for by this pair of objects.

The IRAS colours of SGR1900+14 suggest that the emission is due to cool dust, with a range of temperatures. Can this dust be associated with the two M stars detected in the near-infrared and TIMMI images? At present it is not clear if the M stars are physically related to the extended far-IR emission, they could be foreground objects; in the following discussion we will assume that a physical relation exists. The fact that the two M stars are detected both in the near infrared and at 12 μm indicates that they are not heavily reddened by interstellar or circumstellar dust; from a comparison of their HJK colours (Vrba et al. 1995) with the intrisic colours of M3-type stars (Koornneef 1983) we find $A_V = 12.5 \pm 0.5$. The IRAS 12 μm flux density agrees very well with the combined values for the two M stars seen in the TIMMI data. It is therefore likely that the 12 μm emission is roughly photospheric, with only a small contribution from the extended component. The emission from the M stars is expected to decrease towards longer wavelengths, but in fact the 25 μm flux density is more than double that of 12 μm. The M stars therefore exhibit an IR excess of about a factor 5 at 25 μm, which is probably due to the same extended material seen in the TIMMI image, but whose spatial extent is too small to be resolved by HIRAS.

Cool IR excesses in M giants are usually interpreted as due to emission from a detached envelope, which was ejected during a previous phase of high mass loss. If this interpretation is correct, we would expect that the size of the 25 and 60 μm IRAS sources be similar. However this is clearly not the case (see Table 2). In fact the 60 μm suggests the presence of yet another component of very low temperature (less than 50 K) which is very extended, superimposed on a warmer more compact source seen in the TIMMI image and at 25 μm. In conclusion the IR data suggest that: (i) the 12 μm IRAS flux densities are due to the (photospheric) emission from the two M stars, with a faint extended component; (ii) at 25μm the M stars show an IR excess with a colour temperature less than 100 K; (iii) at 60 μm there is an extended, very cool component in addition to the warm excess component seen at 25 μm.

The fact that the IRAS source is not resolved at 25 μm and rather extended at 60 μm may point to different emission mechanisms responsible for the 25 and 60 μm emission, such as a compact source with warm dust or line emission at 25 μm and a cool extended dust shell at 60 μm. Such an effect is also seen in some planetary nebulae (e.g. Leene & Pottasch 1987). We were able to extract a low S/N IRAS LRS spectrum from the raw data base, but no obvious strong lines were seen.

4. Conclusions

The IR source associated with SGR 0526–66 is extended at 12, 25 and 60 μm. Its emission likely originates from heated dust in the supernova remnant N49, and there is no evidence for a relation of this emission to the presence of the soft gamma repeater at the edge of N49.

The IR morphologies of the two Galactic SGRs are similar: in both cases the emission is point-like at the shorter wavelengths and extended at 60 μm. If we assume that also SGR 0526–66 has this morphology and intrinsic brightness, such a source would not have been detected with IRAS at the distance of the LMC, certainly not if we take into account the presence of the SNR N49. This is consistent with the our conclusion that the IRAS source near SGR 0526–66 is in fact N49.

The 12 and 25 μm properties of SGR 1806–20 are consistent with dust emission from the (unresolved) envelope of the luminous blue variable found by Van Kerkwijk et al. (1995). The IRAS 12 μm flux density of SGR 1900+14 can be accounted for by the emission of the close pair of M-type stars found by Vrba et al. (1995). At 60 μm the sources coincident with both SGR 1806–20 and SGR 1900+14 show extended emission; this indicates the presence of a rather cool emitter distinct from the unresolved 12 μm and 25 μm sources. Thus, with respect to their IR properties the two galactic SGRs are quite similar. Whether, and – if so – how, these unresolved and extended IR components are related to the soft gamma repeaters, is as yet unclear.

To improve our understanding of the soft gamma repeaters we have an ongoing program of multi-wavelength observations, that include spectral, imaging and polarimetric observations using the Infrared Space Observatory, mid- infrared mapping and spectroscopy with the Thermal Infrared MultiMode Instrument at ESO, and submillimeter observations with the James Clerk Maxwell Telescope.

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