ISO–SWS spectroscopy of IC443 and the origin of the IRAS 12 and 25 µm emission from radiative supernova remnants

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Received 17 November, accepted 3 December 1998

Abstract. ISO–SWS spectral observations of the supernova remnant IC443 are presented. Like other radiative SNRs, this object is characterized by prominent line–emitting filaments and relatively strong IRAS 12 and 25 µm emission which is commonly interpreted as thermal radiation from very small grains stochastically heated by collisions with the hot plasma behind the shock front. This interpretation is challenged by the data presented in this Letter which indicate that most of the 12 and 25 µm IRAS flux is accounted for by ionized line emission (mainly [NeII] and [FeII]). This result also seems to hold for other IRAS flux is accounted for by ionized line emission (mainly [NeII] and [FeII]). This result also seems to hold for other

Key words: ISM: individual objects: IC443; ISM: supernova remnants; Infrared: ISM: lines and bands

1. Introduction

A significant fraction of the galactic supernova remnants were detected by the IRAS satellite (e.g. Arendt 1989, hereafter [A89]) and their relatively strong FIR emission has been normally interpreted as thermal radiation from dust which is heated by collisions with the hot (million degrees) plasma in the post–shock region (e.g. Braun & Strom 1987, Dwek et al. 1987). This emission could be an important cooling mechanism for non–radiative shocks in young SNRs (e.g. Ostrik & Silk 1993). The spectral shape of the FIR emission reflects the temperature distribution of the dust which in turn depends on the shock speed and on the density, size and composition of the grains (e.g. Draine 1991). Young SNRs are expected to have a FIR spectrum characterized by a single temperature because, in the hot (∼ 2 × 10^7 K) plasma typical of these objects, the temperatures of collisionally heated dust grains approach the same value independent of grain size (e.g. Dwek 1987). This is in good agreement with the IRAS data of young SNRs (e.g. Cas A, Tycho, Kepler) whose spectral distributions are fairly well fitted by a single temperature blackbody (e.g. [A89]).

The IRAS colours of radiative SNRs are much more complex and require an ad hoc combination of dust components of different sizes and temperatures. In particular, the S12/S25 IRAS colours are much bluer than those of young SNRs and require a very large population of very small (< 50 Å) grains (e.g. Arendt et al. 1992). An alternative explanation is that the flux seen in the “blue” IRAS bands is dominated by line emission from the radiative filaments but this possibility could not be verified directly because of the difficulty of measuring the FIR lines prior to ISO. Attempts to estimate the line contamination by extrapolating optical spectral measurements using shock model predictions have led to contradictory conclusions (e.g. Mufson et al. 1984, Arendt et al. 1992).

In this Letter we present FIR spectral observations of a prototype radiative SNR which allow a direct comparison between the IRAS and line fluxes. The data are presented in Sect. 2, the results are discussed in Sect. 3 and in Sect. 4 we draw our conclusions.

2. Observations and results

A complete SWS01 (speed 4, 6700 sec total integration time) spectrum centered at α=06h14m32.6s δ=−22°54′05″ (1950 coordinates) and roughly corresponding to position 1 of Fesen & Kirshner (1980) was obtained on October 16, 1997. The data were reduced using standard routines of the SWS interactive analysis system (IA) using calibration tables as of October 1998. Reduction relied mainly on the default pipeline steps, plus removal of signal spikes, elimination of the most noisy band 3 detectors, and flat–fielding. Note that SWS has a quite high spectral resolution (R = λ/δλ ∼ 1500) and is not well suited for measure-
ments of faint continuum fluxes. For the SWS01 mode, in particular, s/n and detector drifts between dark current measurements do not allow measurements of continuum emission at levels much below 1 Jy. The measured IRAS 12 and 25 µm “continuum” fluxes from the SNR would correspond to only ≃0.01 Jy in the SWS aperture and cannot therefore be detected with the spectral observations presented here.

The spectral sections including well detected lines are displayed in Fig. 2 and the derived line fluxes are listed in Table 1 together with their contribution to the IRAS fluxes, estimated using the spectral response shown in Fig. 3. The line profiles are not resolved within the noise (i.e. FWHM<400 km/s), and their centroids are not significantly red/blue–shifted.

The most striking result is that the surface brightness of [NeII]λ12.8 alone is larger than that observed by IRAS through the 12 µm filter. This apparent contradiction reflects the somewhat higher spatial resolution of ISO–SWS relative to the undersampled IRAS maps. More specifically, the line emitting filaments visible in the Hα and [SII] images of Mufson et al. (1986) are quite uniformly distributed over many arcmin, i.e. an area larger than the IRAS map resolution, and the average line surface brightness over this area is roughly a factor of 2–4 lower than that within the ISO–SWS aperture. In other words, the ISO spectra, although centered on a bright optical filament, does not sample a spot of exceptionally large line surface brightness, but rather a “typical” line emitting region.

This indicates, therefore, that the IRAS 12 µm “continuum” is indeed dominated by [NeII] line emission, i.e. that this line accounts for at least 50% of the observed IRAS flux. A similar reasoning applies to the IRAS 25 µm flux which is strongly contaminated by emission in the [FeII]λ26.0 ground state transition plus significant contribution from [OIV]λ25.9, [SIII]λ18.7 and [FeII]λ17.9 (cf. Table 1).

Another interesting result is that [FeII]λ26.0/[NeII]λ12.8 and [FeII]λ26.0/[SII]λ34.8 are both a factor of ≃1.7 lower than those observed in RCW103 (Oliva et al. 1998), while the density sensitive [FeII]λ17.9/λ26.0 ratio is similar in the two objects. This result indicates that IC443 has a lower Fe gas phase abundance than RCW103 where the Fe/Ne and Fe/Si relative abundances were found to be close to their solar values. This difference may reflect intrinsic differences in the ISM total element abundances or, more likely, imply that the shock in IC443 is slower and therefore less effective in destroying the Fe–bearing grains. This last possibility is also supported by other “speedometers”, i.e. the line surface brightness and the [NeIII]/[NeII] ratio which are lower by a factor of 7 and 1.6, respectively.
find a total $\text{[NeII]}$ mapped with SWS by Oliva et al. (in preparation). They feasible in the LMC where e.g. the remnant N49 has been

galaxy because of their very large projected sizes, but is impossible in IC443 and other radiative remnants in the

distribution to the IRAS fluxes requires a measurement of the line contribution. The easiest and most direct estimate of the line contribution is shown in Fig. 1.

3. Discussion

The data presented above strongly suggest that most of the 12 and 25 $\mu$m flux from the NE rim of IC443 is due to ionic line emission rather than continuum emission from warm dust. We address here the following questions. Can this result be generalized to other radiative SNRs? Are there other lines which may severely contaminate IRAS measurements of this and other remnants?

3.1. The IRAS 12 and 25 $\mu$m emission from other SNRs

The easiest and most direct estimate of the line contribution to the IRAS fluxes requires a measurement of the FIR line intensity from the whole SNR. This is virtually impossible in IC443 and other radiative remnants in the Galaxy because of their very large projected sizes, but is feasible in the LMC where e.g. the remnant N49 has been mapped with SWS by Oliva et al. (in preparation). They find a total $|\text{[NeII]}|\lambda 12.81$ line intensity of $2 \times 10^{-14}$ W m$^{-2}$ and equal, within the errors, to the $|\text{F}(12\mu m)|=2.2 \times 10^{-14}$ W m$^{-2}$ IRAS flux reported by Graham et al. (1987).

For remnants where direct measurements of FIR lines is not available, a reasonable estimate of their fluxes can be obtained by scaling optical line measurements using available ISO spectral observations of radiative SNRs, namely IC443 (this paper), RCW103 (Oliva et al. 1998) and N49 (Oliva et al. in preparation). These indicate that the $|\text{[NeII]}|$ and $|\text{[FeII]}|+|\text{[SIII]}|+|\text{[OIV]}|$ line contribution to the 12 and 25 $\mu$m filters are both roughly equal to the flux of H$\beta$. Unfortunately, relatively few optical spectrophotometric observations of SNRs are available in the literature and are altogether missing for several important radiative remnants such as W44 and W49B. Nevertheless, the SW filament of RCW86 has $\Sigma(H\beta) \simeq 4 \times 10^{-7}$ (Leibowitz & Danziger 1983) and very similar to the $\Sigma \simeq 3 \times 10^{-7}$ W m$^{-2}$ sr$^{-1}$ IRAS 12 and 25 $\mu$m fluxes found by A89. Similarly, the NE filament of the Cygnus Loop has $\Sigma(H\beta) \simeq 1 \times 10^{-7}$ (Fesen et al. 1982) and close to the IRAS surface brightness $\Sigma \simeq 8 \times 10^{-8}$ W m$^{-2}$ sr$^{-1}$ (A89). These results suggest, therefore, that lines account for most of the IRAS 12 and 25 $\mu$m emission from line emitting filaments of radiative SNRs.

Another interesting exercise is to compare optical line and IRAS fluxes in a younger remnant such as the Kepler SNR for which accurate line photometric measurements are available (D’Odorico et al. 1986). The total H$\beta$ emission from the whole remnant is $2.9 \times 10^{-15}$ W m$^{-2}$ and only 2% and 0.6% of the IRAS flux in the 12 and 25 $\mu$m bands, respectively. This indicates, therefore, that line contamination is negligible in this object.

3.2. Contamination from other lines

The positions of the most important lines are marked in Fig. 3 where one can see that $|\text{[SIII]}|\lambda 34.8$, although very prominent in SNRs, does not contribute significantly because it falls at a wavelength where IRAS was virtually blind. The same applies to $|\text{[NeIII]}|\lambda 15.6$ which has an intensity comparable to $|\text{[NeII]}|$ but falls in the hole between the 12 and 25 $\mu$m filters.

The possible contribution of $|\text{[OI]}|\lambda 63.0$ to the IRAS 60 $\mu$m band was already pointed out by Burton et al. (1990).

Table 1. Observed ISO line fluxes

| Line          | Flux$^{(1)}$ | Shit$^{(2)}$ | $\Sigma$-IRAS$^{(3)}$ |
|--------------|-------------|--------------|----------------------|
| $|\text{[NeII]}|\lambda 12.81$ | 18 (3) | $14 \times 27$ | 20 | – | – |
| $|\text{[NeIII]}|\lambda 15.66$ | 10 (2) | $14 \times 27$ | – | – | – |
| $|\text{[FeII]}|\lambda 17.93$ | 4 (1) | $14 \times 27$ | – | 2 | – |
| $|\text{[SIII]}|\lambda 18.71$ | 4 (2) | $14 \times 27$ | – | 3 | – |
| $|\text{[OIV]}|\lambda 25.88$ | 3 (1) | $14 \times 27$ | – | 3 | – |
| $|\text{[FeII]}|\lambda 25.98$ | 8 (1) | $14 \times 27$ | – | 10 | – |
| $|\text{[SIII]}|\lambda 34.8$ | 52 (7) | $20 \times 33$ | – | – | 2 |

Observed IRAS fluxes$^{(a)}$: 10 10 60

$^{(1)}$ Observed line flux, units of $10^{-16}$ W m$^{-2}$, errors are given in parenthesis.

$^{(2)}$ Size (in arcsec) of the SWS apertures.

$^{(3)}$ Equivalent surface brightness in the IRAS bands, units of $10^{-12}$ W m$^{-2}$ sr$^{-1}$.

$a$ Observed IRAS surface brightness at the position of the SWS aperture, estimated from Fig. 30a of A89, see also Fig. 1.

Fig. 2. Selected sections of the SWS01 spectrum of the north-east rim of IC443, note that each spectral segment has been “continuum subtracted” (using a $\leq 2$ degree polynomial) to remove instrumental offsets and drifts. The position of instrument aperture is shown in Fig. 1.
who observed this line in the southern (“molecular”) rim of IC443 using a 33” aperture spectrometer on the KAO and found line surface brightnesses a factor of \(\sim 2\) larger than those measured by IRAS. On the other hand, however, ISO–LWS measurements of [OI] \(\lambda 63.0\) through a \(\Theta 80”\) aperture centered on the optical filaments of W44 (Reach & Rho 1996) yield a line surface brightness a factor of \(\sim 2.5\) lower than the IRAS 60 \(\mu m\) flux indicating, therefore, that the contamination by [OI] is relatively unimportant, at least in this remnant.

The \(H_2\) rotational lines could strongly affect the 12 \(\mu m\) band and may explain why the \(S(12)/S(25)\) ratio is a factor of \(\sim 2.5\) larger on the southern rim of IC443, i.e. at \(\sim 06^h14^m40^s +22^\circ 23’\) (cf. Fig. 2). This region is a well known powerful source of \(H_2\) \((1,0)S(1)\lambda 2.12\) line emission (Burton et al. 1988) whose spatial distribution closely resembles the IRAS 12 \(\mu m\) contours. Ground–based observations of the \((0,0)S(2)\lambda 12.3\) rotational transition were obtained by Richter et al. (1995) who measured a line flux \(\sim 10\) times brighter than \((1,0)S(1)\lambda 2.12\). Assuming a constant \(I(12.3)/I(2.12)\) ratio over the large area mapped in the latter transition by Burton et al. (1988) yields an average line surface brightness of about \(1.5 \times 10^{-7}\) W m\(^{-2}\) sr\(^{-1}\) or 1/3 of the IRAS 12 \(\mu m\) peak surface brightness.

Considering that the \(H_2\) spectrum of IC443 is remarkably similar to that of Orion peak1 (e.g. Richter et al. 1995) one then expects similar fluxes in the \((0,0)S(3)\lambda 9.66\) and \((0,0)S(2)\lambda 12.3\) lines (Parmar et al. 1994) or, equivalently, that the two lines should account for about 2/3 of the IRAS 12 \(\mu m\) flux.

Finally, it should be noted that IRAS was virtually blind to the \(H_2(0,0)S(1)\lambda 17.0\) line (cf. Fig. 3) while the highly forbidden ground state transition \((0,0)S(0)\lambda 28.2\) is most probably too weak to significantly contaminate the 25 \(\mu m\) IRAS band (cf. e.g. Fig. 2 of Oliva et al. 1998).

4. Conclusions

An ISO–SWS spectrum of IC443 has revealed prominent [NeII] and [FeII] line emission which, together with [SIII] and [OIV], account for most of the observed IRAS flux in the 12, 25 \(\mu m\) bands. Simple arguments indicate that this is probably the case in other radiative SNRs and this result suggests that the unusually blue IRAS colours of radiative SNRs simply reflect line contamination, rather than a large population of small grains which are otherwise required to explain the warmer “continuum” emission. Available ground based data also indicate that \(S(2), S(3)\) rotational lines of \(H_2\) contribute to a large fraction of the IRAS 12 \(\mu m\) emission from the southern rim of IC443.

The relative fluxes of the ionic lines detected by ISO yield a \(\sim 0.6 \times \) solar Fe gas–phase relative abundance which is significantly lower than that found in the much more powerful RCW103 supernova remnant. This may imply that the shock in IC443 is slower and thus less effective in destroying the Fe–bearing grains. This scenario is also supported by the lower line surface brightness and \([NeII]/[NeII]\) ratio which both indicate a lower shock speed in IC443.

Acknowledgements. We thanks the referee, R. Arendt, for useful comments and criticisms.

E. Oliva acknowledges the partial support of the Italian Space Agency (ASI) through the grant ARS–98–116/22.

SWS and the ISO Spectrometer Data Center at MPE are supported by DLR (formerly DARA) under grants 50–QI–8610–8 and 50–QI–9402–3.

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\(^1\) Note that the “continuum” in the LWS spectra of W44 by Reach & Rho (1996) is most probably an instrumental artifact, its level being 10 times brighter than the IRAS 60 \(\mu m\) background+source flux.
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