INFRARED ANALYSIS OF SUPERNOVA REMNANTS

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Abstract. Infrared observations of supernova remnants obtained with the Infrared Astronomical Satellite provide new insights into the dynamics and energetics of the remnants, and into their interaction with the ambient interstellar medium. In most remnants the infrared emission arises from dust that is collisionally heated by the X–ray emitting gas. The infrared observations can therefore be used as a diagnostic for the physical conditions of the shocked gas. In particular, it is shown that all the prominent X-ray remnants in the Galaxy and in the LMC cool mainly by dust grain collisions instead of atomic processes.

1. Introduction

Theoretical calculations (Ostriker and Silk 1973; Silk and Burke 1974) suggest that at temperatures above ~ 10^6 K, a dusty plasma should cool mainly at infrared (IR) wavelengths. Supernova remnants (SNR) should therefore appear as prominent IR sources in the galaxy. However, searches for IR emission from Tycho, Kepler, and Cas A (Wright et al. 1980), and the Crab Nebula (Harvey et al. 1978), yielded essentially negative results. Searches for IR emission from the optical knots in Cas A, which were suggested by Dwek and Werner (1981) as possible sites of supernova condensate material, were more successful (Dinerstein et al. 1987). However, the detected radiation has been attributed to IR line emission from ionic species present in the shocked optical nebulosities of Cas A.

This situation has drastically changed with the success of the Infrared Astronomical Satellite (IRAS) which in November 1983 completed an unbiased all-sky survey at 12, 25, 60, and 100 μm. Details on the instrument, observing strategy, and mission objectives can be found in Neugebauer et al. (1984), the first paper in a special Ap. J. Letters issue dedicated to the IRAS mission. In the same issue, Marsden et al. (1984) reported the first detection of IR emission from dust in a SNR, the Crab Nebula. Figure 1, taken from Mezger et al. (1986), shows the spectrum of the IR and radio emission from the Crab. The Crab has a strong non-thermal radiation field that fills the nebula, and the figure clearly shows the thermal IR emission just barely rearing its peak above this nebular emission component. Dwek and Werner (1981) have shown that in the Crab the dust is most likely to be radiatively heated by the ambient radiation field. The Crab nebula may therefore represent a special class of SNR in which the IR emission represents only a minor fraction of the total radiative output from the remnant.

The opposite is true of the emission of all other remnants that will be discussed in this review. Figure 2 (based on Dwek et al. 1987a) depicts the power emitted by Cas A from radio to X-ray wavelengths. The figure shows that most of the radiative output of the remnant is at IR wavelengths. The dust is most likely of interstellar origin and collisionally heated by the shocked gas.

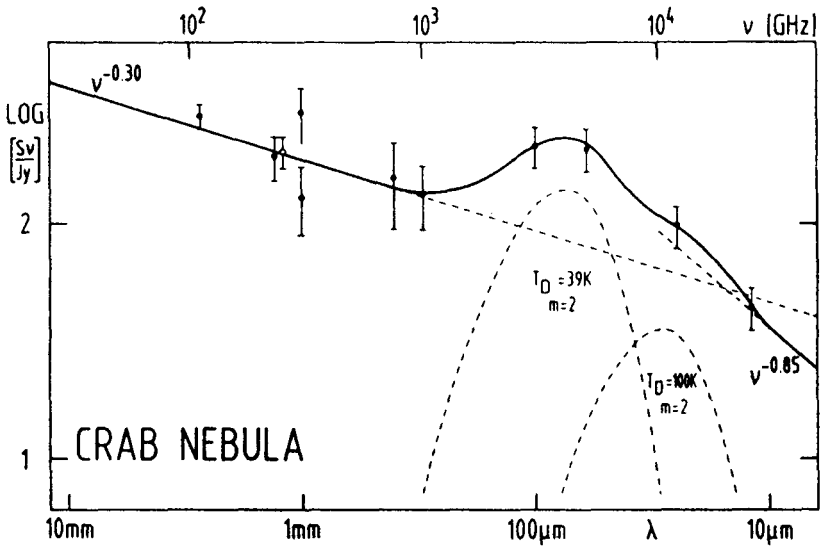

Figure 1 – *The spectrum of the Crab Nebula as presented by Mezger et al. 1986. The dust is radiatively–heated in the Crab, and its IR emission represents only a small fraction of the total radiative output from the nebula.*

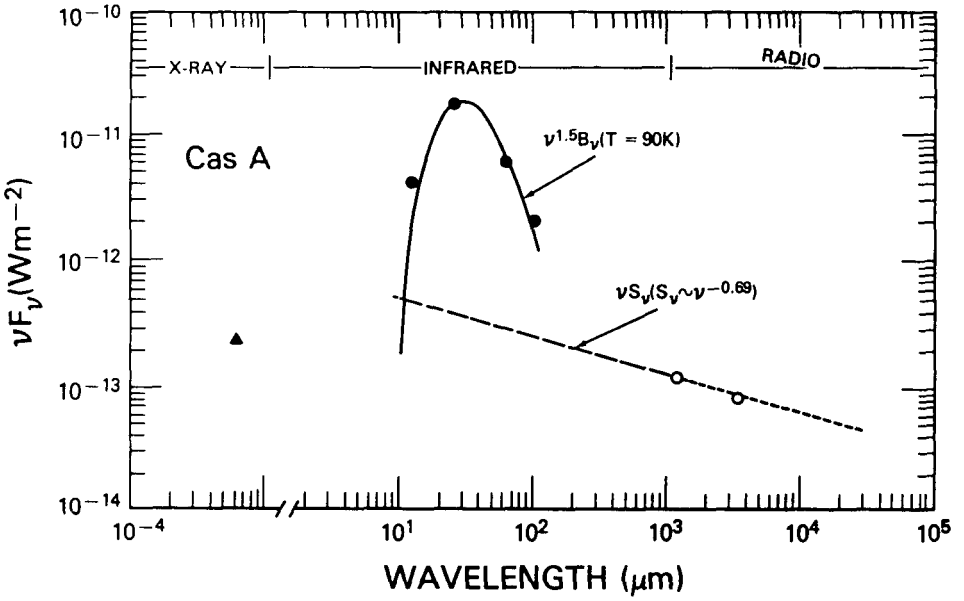

Figure 2 – *The power spectrum of Cas A. The dust is collisionally–heated in the remnant, and its IR radiation dominates the emission at all other wavelengths.*

The most extensive search for SNR in the IRAS skyflux plates is being conducted by Arendt (1987a). From a preliminary unbiased sample of 70 remnants, identified by their radio emission, 16 showed evidence for IR emission that is clearly associated with the remnant, and 24 sources showed evidence for IR emission, but its association with the remnants is uncertain. The remaining 30 regions showed no evidence for IR emission that could be attributed to the remnant. This investigation shows that the IR detection of SNR is mostly hampered by confusion with other IR

objects near the galactic plane. The latter is suggested by preliminary findings that the average galactic lattitude of the remnants detected in the search is $|b|=2.0^{o}$, whereas remnants with no detectable IR emission seem to be located closer to the plane with an average value of $|b|=0.8^{o}$. However, some remnants elude detection even though they are high-lattitude objects, and are therefore expected to figure quite prominently in the IRAS skyflux plates. An example of such a remnant is SN 1006 (l; b = 327.5^{o}; +14.6^{o}) which is expanding into a low-density interstellar medium (ISM). This suggests that a minimum ISM density is required to observe the IR emission from shock heated dust (Dwek et al. 1987b; Braun 1986a).

In the remainder of this review I will emphasize remnants that are most prominent in the IR. Multiwavelengths analysis of these remnants have been presented in a series of papers: Tycho, Kepler, and Cas A (Braun 1987), Cas A (Dwek et al. 1987a); IC443 (Braun 1986b; Mufson et al. 1986; McCollough and Mufson 1987); Cygnus Loop (Braun 1986c); and G292.0+1.8 (Braun 1986a). For these remnants, the IRAS observations constitute the first observational evidence of collisionally heated dust in the ISM. The IR emission may therefore be used as a diagnostic for the plasma conditions in the remnant , and a new means for deriving various parameters that determine its evolution.

2. Infrared Emission Mechanism

The galaxy is transparent at wavelengths of the IRAS bands. Therefore, several dust components not associated with the remnant may contribute to the IR flux from the direction of the remnant. These include: 1) emission from interplanetary dust particles (zodiacal dust); 2) emission from interstellar dust; 3) infrared cirrus; and 4) any galactic or extragalactic extended or point sources. Any attempt to analyze the IR emission from the remnant must therefore be preceded by a separation of all these various emission components.

Figure 3 – *A composite image of the Cygnus Loop at 60 μm (outer contour lines), X-ray (light shaded area), and optical wavelengths (dark shaded areas).*

The main zodiacal emission component (described by Hauser et al. 1984) has a flat spatial

6. Effect on Remnant Evolution

An important question is - will the IR cooling of the remnants accelerate their evolution compared with the standard evolutionary picture presented, for example, by Cox (1972)? The first evolutionary stage of the remnant is the free expansion phase, terminated when enough mass has been swept up to begin decelerating the shock. This stage is not affected by radiative processes behind the shock. The second stage of remnant evolution, the adiabatic phase, is terminated when about half of the thermal energy of the remnant has been radiated away. The end of this phase is marked by the formation of a dense shell behind the shock and the beginning of the "snowplow" phase of remnant evolution. Enhanced cooling resulting from gas-grain collisions may therefore significantly affect the duration of the adiabatic phase.

The importance of dust cooling depends on the density of the ISM, and can be qualitatively assessed in the following way: Consider a remnant with $E_o=10^{51}$ erg expanding into an ISM with $n_o=1$ cm^{-3}. The postshock temperature at the end of the adiabatic phase, T_c, is about 5×10^5 K, whereas IR emission dominates the cooling of the remnant when $T > 6\times10^5$ K (see Figure 4). Gas-grain collisions will therefore have only a moderate effect on the duration of the adiabatic phase, since most of the thermal energy is lost from the remnant when its volume is largest (i.e. around temperatures of $\sim 6\times10^5$ K when IR and atomic cooling are about equally important). At densities of $n_o=100$ cm^{-3}, T_c is about 2×10^6 K, so that most of the thermal energy is lost when IR emission dominates the cooling by a large factor. Calculations by Dwek (1981) show that the adiabatic phase is shortened by only ~ 10% in the former case, and by as much as ~ 40% in the latter case. At higher densities, IR cooling should be more pronounced. However, grain destruction becomes increasingly important as well, resulting in declining effect of gas-grain collisions on remnant evolution. All adiabatic remnants considered here expand into media with densities < 10 cm^{-3} , so that the IR emission will have a negligible effect on their general evolution. However, as suggested by Graham et al. (1987), the IR emission will affect the internal temperature structure of the remnant.

7. Future Prospects

The IRAS all sky survey opened a new wavelength window for the studies of SNR. An interesting question is whether SNR form a class of IR objects that is distinct from other known IR sources like HII regions or planetary nebulae. Such a distinct spectral 'signature' will prove valuable in the identification of SNR that may explode in molecular clouds (Shull 1980; Wheeler, Mazurek, and Sivaramakrishnan 1980). The preliminary investigation of Arendt (1987a) shows that the IR spectrum of an 'average' SNR peaks between the 60 and 100 μm bands of the IRAS, or that it is still rising at 100 μm. The spectrum of these remnants is therefore essentially identical to that of compact HII regions. Planetary Nebulae are hotter objects with IR spectra that peak between 25 and 60 μm (e.g. Pottash 1984). They are therefore distinctly different from the average SNR but look very similar to young remnants like Tycho, Kepler, and Cas A. The lack of any unique IR spectral signature and the confusion with IR sources near the galactic plane suggest that the most promising approach to discover new SNR is still to search for their radio emission (Caswell 1987).

However, even if the IR cannot currently be used to identify new remnants, it provides researchers with powerful means to study the dynamics and energetics of existing remnants, and their interaction with the ambient interstellar medium. A stepwise approach to such analysis would include the following: removal of zodiacal, galactic, and cirrus emission components from the IR image of the remnant; analysis of the relative contribution of IR lines and continuum radiation to the emission; comparison between the IR and X-ray emission to estimate the contribution of collisionally-heated dust to the emission; comparison between IR and optical, HI, and CO maps of

the region to estimate the contribution of IR lines from shock–heated filaments or clouds; search for adjacent OB associations to estimate the relative contribution of radiatively–heated dust to the emission. This outline shows the intricate relation between studies at the various wavelengths at our disposal, a collection of which IR radiation is the newest member.

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