A Near-IR [Fe II] Line Imaging Survey of Supernova Remnants in M 33

Thierry Morel,[1] René Doyon,[2] & Nicole St-Louis[2]

[1] Astrophysics Group, Imperial College of Science, Technology and Medicine, Blackett Laboratory, Prince Consort Road, London, SW7 2BZ, UK; t.morel@ic.ac.uk.
[2] Département de Physique, Université de Montréal, C. P. 6128, Succ. Centre-Ville, Montréal, Québec, Canada, H3C 3J7; and Observatoire du Mont Mégantic; doyon, stlouis@astro.umontreal.ca.

Abstract. We report on the first near-IR [Fe II] line imaging survey of extragalactic SNRs. Observations of a sample of 42 objects drawn from an optically-selected catalogue of SNRs in M 33 provide evidence for a wide range in the [Fe II] $\lambda 1.644$ μm luminosities. This can be understood as being primarily due to variations in the chemical abundances and density of the local ISM, although shock conditions may also play a significant role. We briefly discuss how these results may be used to better calibrate the supernova rate of star-forming galaxies.

1   Why this survey?

The use of the strong near-IR [Fe II] lines as a mean of estimating the supernova rate of starburst galaxies has become increasingly popular over the last decade (e.g., Calzetti 1997). However, one serious limitation of this technique lies in the fact that one has to adopt typical values for the [Fe II] luminosity and [Fe II]-emitting lifetime of a *single* supernova remnant (SNR), whereas a wide span of values are observed. For instance, the [Fe II] luminosities of SNRs in the starburst galaxy M 82 (Greenhouse et al. 1997) are two orders of magnitude higher than in "quiescent" galaxies, such as our Galaxy or the LMC (Oliva et al. 1989). One order of magnitude higher values are also observed in NGC 253 (Forbes et al. 1993). Therefore, before applying this technique to star-forming galaxies that presumably exhibit widely different properties (e.g., metallicity), one must first understand what parameters control the [Fe II] properties of individual SNRs. In an effort to address this issue, we report here on preliminary results of a [Fe II] $\lambda 1.644$ μm line imaging survey of an heterogeneous sample of SNRs in M 33.

2   Observations

Our observations were obtained during two observing runs at the Canada-France-Hawaii telescope (*CFHT*) in 1997 and 1998. Two different infrared cameras were used: *MONICA* in 1997 and *REDEYE* in 1998. A total of 42 objects drawn from the optically-selected atlas of Gordon et al. (1998) has been observed. Particular attention has been paid to observe SNRs with widely different properties. The standard reduction procedure for infrared imaging has been applied (see, e.g., Hodapp et al. 1992).

3   Relationship between the [Fe II] emission and other SNR properties

The broad range of [Fe II] $\lambda 1.644$ μm luminosities is made clear by the fact that — while several SNRs present an outstanding level of [Fe II] emission (see Fig.1) — many of them remain undetected in our survey.
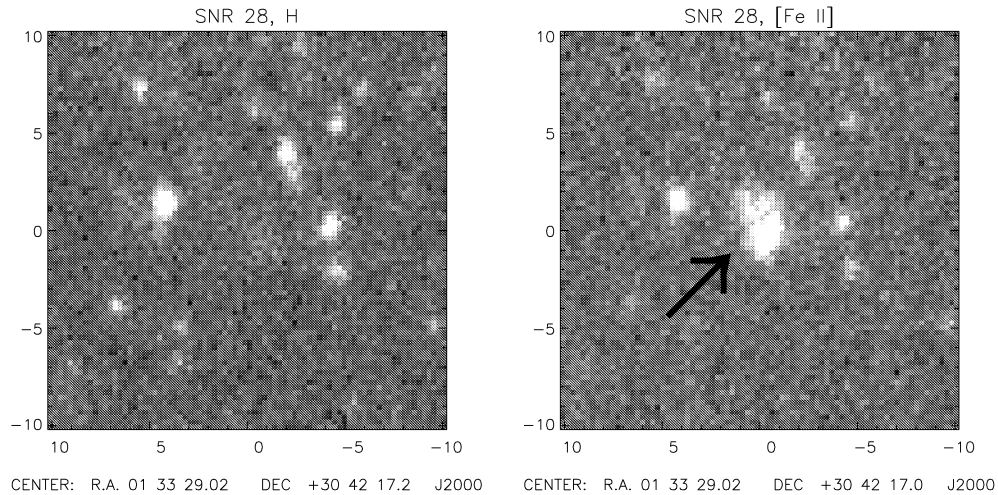
Fig. 1. Comparison of the *H* (*left panel*) and [Fe II] $\lambda 1.644$ μm (*right panel*) images of SNR 28 (identification from Gordon et al. 1998). The SNR is indicated by an arrow. The field of view is $20'' \times 20''$. North is up, and east is to the left. The integration times are 300 s and 1 500 s for *H* and [Fe II], respectively.

The [Fe II] $\lambda 1.644$ μm luminosities (or upper limits) are presented in Table 1. It can be seen that a (nearly) two orders of magnitude range is observed in these values. Lumsden & Puxley (1995) reported near-IR spectroscopic observations of 9 of our program targets. There is a good agreement between the two estimates.[1]

In order to pin down the physical processes that produce the [Fe II] emission, we sought for correlations between the [Fe II] $\lambda 1.644$ μm luminosities and various quantities intrinsic to the SNRs, such as their age or optical-line properties, for instance. We made use of the generalized Kendall's tau correlation technique which allows us to investigate statistical correlations between datasets including upper limits (Isobe, Feigelson, & Nelson 1986). Table 2 summarizes the results of this statistical analysis for all quantities under consideration, along with the source of these data.

In a preliminary effort to calculate the dynamical age of the SNRs, we have simply assumed that they all undergo Sedov-Taylor expansion, as suggested by Gordon et al. (1998). Without a detailed knowledge of the evolutionary status, initial blast energy of the SNR, and of the ambient gas density in which it evolves, age estimates are notoriously uncertain. Therefore, the complete lack of any relationship between the level of [Fe II] emission and the dynamical age of the remnant (see Table 2) should be treated at this stage of the data analysis with caution.

Our data support the idea that environmental rather than evolutionary effects are more important in controlling the [Fe II] properties. A tight correlation is found between the electronic densities derived from the [S II] $\lambda\lambda 6717, 6731$ doublet and L([Fe II] $\lambda 1.644$ μm). This confirms that the [Fe II] emission arises in the dense postshock region. The brightest [Fe II] remnants are characterized by n_e([S II]) $\approx 10^3$ cm^{-3}, which translates to n_e([Fe II]) $\approx 10^{3.5}$ cm^{-3} (e.g., Lumsden & Puxley 1995). This requires preshock densities significantly higher than canonical values for the ISM ($n_e \approx$ 0.1-10 cm^{-3}), approaching values typical of molecular material. Radio emission from SNRs is due to synchrotron emission, and is thus primarily a function of the magnetic field strength. The (weak) correlation between S_{20} and n_e (Table 2) is expected given that the magnetic field strength scales with density (see Brogan et al. 2000). The tendency for the objects with high radio fluxes to be strong [Fe II] emitters may be thus secondary in nature, and merely reflect the fact that dense environments both enhance the [Fe II] and radio emission.

A tight correlation is also observed between L([Fe II] $\lambda 1.644$ μm) and the generalized "metal

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[1]Their [Fe II] $\lambda 1.257$ μm fluxes have been converted into [Fe II] $\lambda 1.644$ μm fluxes assuming a ratio: [Fe II] $\lambda 1.257$ μm/[Fe II] $\lambda 1.644$ μm = 1.36 (Nussbaumer & Storey 1988).

Table 1. [Fe II] $\lambda 1.644$ μm luminosities of SNRs in M 33.[a]

SNR Id.[b]	L ([Fe II] $\lambda 1.644$ μm) ($L_\odot$)	SNR Id.[b]	L ([Fe II] $\lambda 1.644$ μm) ($L_\odot$)	SNR Id.[b]	L ([Fe II] $\lambda 1.644$ μm) ($L_\odot$)
9	59.9 ± 37.2	25	70.6 ± 28.6	50	< 432
10	< 203	26	< 374	54	< 92.2
12	< 189	28	475 ± 105	55	280 ± 98
13	< 61.0	29	< 94.1	57	< 225
14	< 300	30	< 163	58	< 228
15	< 694	31	671 ± 208	60	< 19.5
16	< 1039	32	< 836	66	< 616
17	< 651	34	< 207	73	< 337
18	< 53.8	35	695 ± 217	74	< 1040
20	< 17.8	38	< 85.8	80	< 306
21	< 174	41	< 2349	82	< 230
22	< 335	43	< 192	86	< 244
23	< 1142	44	< 142	87	< 103
24	< 72.3	45	< 116	94	189 ± 51

[a] Assuming a distance to M 33 of 840 kpc (Freedman, Wilson, & Madore 1991). The upper limits are quoted for a statistical significance of 3σ. The error bars for the detected objects are 1σ uncertainties.
[b] Identifications from Gordon et al. (1998).

abundance", A, as defined by Dopita et al. (1984). This most likely indicates that [Fe II] emission is enhanced in regions characterized by high ISM chemical abundances. Because of the substantial metallicity gradient of M 33 (Garnett et al. 1997), we should therefore observe a strong negative correlation between L([Fe II] $\lambda 1.644$ μm) and the SNR galactocentric distance. However, such evidence is lacking in our data (false alarm probability of 8.5 %), probably owing to the large scatter in the GCD-metallicity relation (Smith et al. 1993). Although iron-bearing grains are easily destroyed by shocks (Draine & Salpeter 1979), both theory and observations suggest that the efficiency of this process may vary from one SNR to another (Jones, Tielens, & Hollenbach 1996; Oliva et al. 1999). The observed correlation between A and L([Fe II] $\lambda 1.644$ μm) may also suggest that [Fe II] emission is favoured by strong shocks that return a large fraction of the dust grains into the gas phase. In this case, we should expect a correlation between the [Fe II] $\lambda 1.644$ μm luminosities and the expansion velocity V_{bulk} (to first order proportional to the shock speed). This correlation is also not clear in our data, possibly because our range of observed V_{bulk} is not broad enough. Different electronic densities can also introduce noise in the correlation.

Although [Fe II] $\lambda 1.644$ μm is believed to probe somewhat cooler, denser material than the optical [S II] doublet (e.g., Oliva et al. 1989), the correlation between the [Fe II] $\lambda 1.644$ μm and [S II] fluxes suggests that the line-formation regions of these two species are not drastically different and that similar physical processes give rise to both emissions. All optical-line fluxes correlate extremely well with L([Fe II] $\lambda 1.644$ μm).

4   Discussion

In the light of the results presented above, we conclude that density and (possibly to a less extent) abundance effects are likely to play a pivotal role in controlling the [Fe II] emission in SNRs. This may help to understand the differences that exist between the near-IR [Fe II] properties of SNRs in galaxies with moderate star-formation activity (such as M 33) and starburst galaxies. While the present study demonstrates that the brightest remnants have luminosities of the order of 700 $L_\odot$, SNRs in the starburst galaxy M 82 have luminosities up to 1.6×10^5 $L_\odot$ (Greenhouse et al. 1991,

Table 2. Results of the statistical analysis. N: Number of points included in the calculations. $\mathcal{P}(X, Y)$: Probability for a chance correlation between the variables X and Y. Note that the objects at large galactocentric distances, GCD, show a tendency for *lower* $L([\text{Fe II}]\ \lambda 1.644\ \mu\text{m})$ values.

X	Y	N	$\mathcal{P}(X, Y)$
$L([\text{Fe II}]\ \lambda 1.644\ \mu\text{m})$	GCD^a	42	8.5 %
"	$n_e{}^a$	34	0.1 %
"	Dynamical age^a	42	82 %
"	Metal abundance^b	20	0.2 %
"	$V_{bulk}{}^c$	8	8.3 %
"	$\mathcal{F}\,([\text{S II}]\ \lambda 6717)^d$	34	0.1%
"	$S_6{}^e$	35	1.5 %
"	$S_{20}{}^e$	35	2.2 %
$n_e{}^a$	$S_{20}{}^e$	34	5.6 %

[a]: From Gordon et al. (1998). The dynamical ages have been derived using their quoted optical diameters.

[b]: From Blair & Kirshner (1985) and Smith et al. (1993).

[c]: From Blair, Chu, & Kennicutt (1988).

[d]: From Smith et al. (1993), Gordon et al. (1998), and Blair & Kirshner (1985).

[e]: From Duric et al. (1993) and Gordon et al. (1999).

1997). Although it remains to be seen whether the two samples trace two similar populations of SNRs, we propose that this dichotomy may be explained by the dense, dusty environments prevailing in the nuclear regions of these galaxies. In particular, it is conceivable that processing (via grain destruction) of the large reservoir of dust grains greatly enhances the [Fe II] emission with respect to more dust-free galaxies.

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