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J.R. Graham, G.S. Wright, and A.J. Longmore

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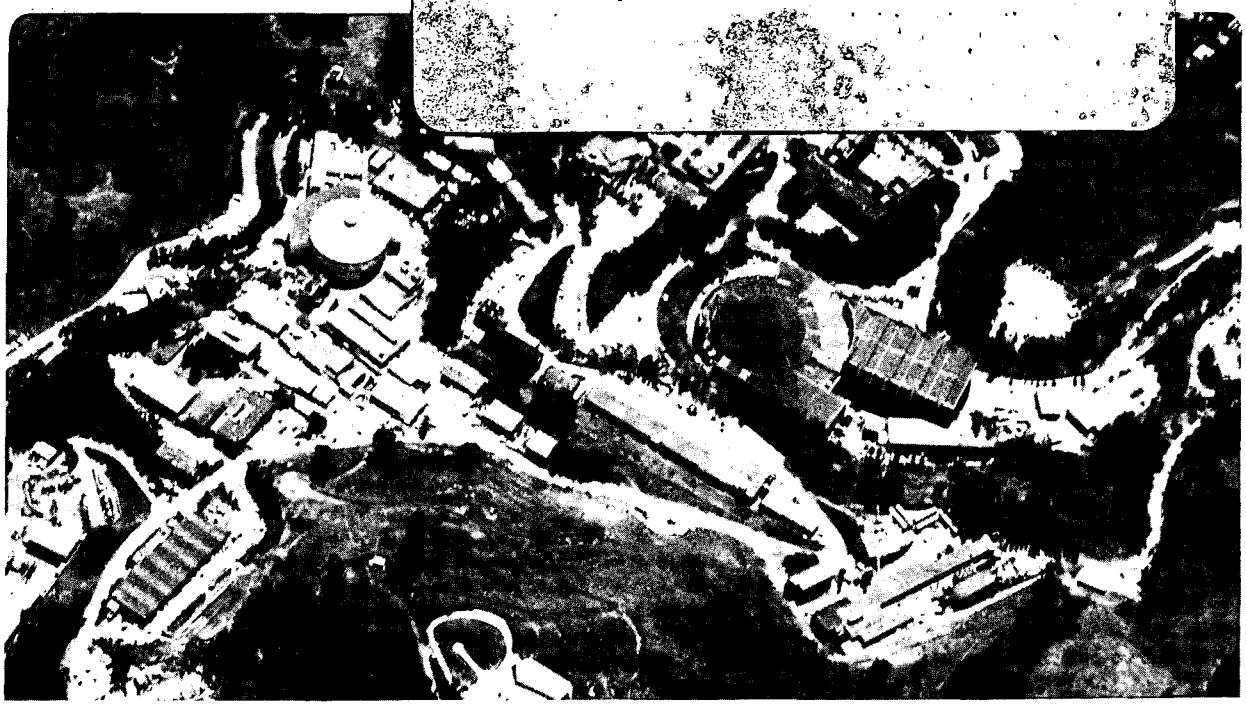

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Infrared spectroscopy of the Supernova Remnant IC443

James R. Graham[1,2]

Gillian S. Wright[2] and Andy J. Longmore[2]

[1] Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720 U.S.A. working under U.S. Dept. of Energy Contract No. DE-AC03-76SF00098.

[2] Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, Scotland, U.K.

Abstract

We present infrared spectroscopy of IC443. The following lines were detected at various positions; [Fe II] 1.644μm, Brackett γ and H_2 1-0 S(1). The most striking feature of the spectra is the [Fe II] 1.644μm /Brackett γ ratio, which is typically ~30. In an HII region we expect a [Fe II] 1.644μm/Brackett γ ratio of ~0.06. We show that the high [Fe II] 1.644μm /Brackett γ ratio in IC443 is due to shock excitation, and argue that measurement of IR [Fe II] lines is a sensitive new probe for shocked gas, especially where the extinction to the emitting region is high, or the shocks are too slow to excite optical lines.

I. Introduction

There is much evidence for shock activity in the interstellar medium. Supernova remnants constitute an important example, but supersonic flows are also found in regions of starformation and galactic nuclei. Spectroscopy is an important diagnostic for these violent motions. Optical spectroscopy is a well established tool for the study of fast shocks (~100km/s). However, there is a clear need to establish a diagnostic for slower shocks which are driven into denser gas. Low excitation infrared (IR) lines, which do not suffer from the extinction which obscures optical lines, would seem to be a natural choice. Since the intensity of the shock radiation scales with the density, the brightest shocks will be observable only in the IR.

Although much of the shock energy is radiated through forbidden IR lines such as [OI] 63μm, and [Si II] 34.8μm, observation of these lines presents formidable problems. Shocks in dense clouds also excite a rich spectrum of molecular rotation/vibration transitions. In particular H_2 emission is readily detected from the ground. Unfortunately interpretation of H_2 spectra is complicated by the fact that H_2 is often observed in shocks where simple arguments would indicate that the molecule should be destroyed at the shock. The poorly characterized processes of destruction and formation an excitation of the molecule must be considered if the emission is to be fully understood. Consequently, a low excitation IR ionic line which is bright in shocks, and

falls in one of the near infrared windows would be a valuable shock diagnostic.

The forbidden IR lines arising from the low lying levels of the Fe II ion satisfy these critera. The excitation temperature of the upper term of the IR multiplets, which fall in atmospheric windows at 1.2 and 1.6 μm, is 2-3 times lower than of the optical lines and critical densities for these [Fe II] lines are ~ 10 times higher. The IR [Fe II] lines hold the potential to be a superior probe of slow shocks in dense material.

The supernova remnant IC443 is an excellent object for developing IR spectroscopy as a shock diagnostic. In this object the supernova blast wave is interacting with interstellar material of a variety of densities at different positions around the SNR shell. A 800km/s shock is propagating into intercloud material of density of 0.5 cm^{-3} giving rise to x-ray emission (Parkes *et al.*. 1977). There are optical line emission filaments excited by 65-100 km/s shocks in clouds of density 10-20 cm^{-3} (Fesen & Kirshner 1980), and slower shocks ~ 30km/s are seen where the remnant has collided with a molecular cloud (Cornett *et al.*. 1977). Further evidence for this interaction can be inferred from the detection of vibrationally excited H_2 molecules (Treffers 1979, Burton *et al.* 1986).

This paper represents the first stage of our study of IC443 in which the 1.644 μm [Fe II] line is reported in fast optically bright shocks. The utility of [Fe II] spectroscopy for studying slow dense shocks where H_2 is present is given credence by the detection of the H_2 1-0 S(1) line and the 1.644μm line in the same aperture.

II. Observations

Infrared spectroscopy in the H and K atmospheric windows was obtained with UKIRT and the common user infrared photometer UKT9, which is equipped with a circular variable filter of resolution ~ 100. The spectra were obtained using a 19.6" diameter circular aperture. Standard chopping and nodding techniques were used to subtract the sky background.

The first exploratory observations of IC443 were made on February 20, 1985. Spectra were obtained on the optically bright north-eastern rim of the remnant at RA $6^h14^m37.7^s$ DEC $+22^o$ 50'46" (epoch 1950). This will be referred to as position A. A north-south chop of 2' was used. Atmospheric absorptions were removed by ratioing the spectra with the featureless spectrum of the F5 IV star HR2706, and then multiplying by a blackbody of the same temperature (6500K). Flux calibration was determined by measuring spectra of the UKIRT photometric standard HD84800. The wavelength calibration was determined by measuring the position of Brackett series lines in the spectrum of the planetary nebula IC418. Figure 1 shows the reduced spectrum. The wavelengths and fluxes of detected lines are given in Table 1.

Further spectra of IC443 were obtained at UKIRT on January 31, 1986. The same photometer was used once again with a 19.6" aperture, and identical data reduction techiques were employed. This time H and K spectra were ratioed with HR2134 (G7 III) and HR2569 (G0 V) respectively. We also observed the flux standards HD84800 and HD44612, and the planetary nebula NGC3242.

The 1986 spectra were measured at points in the remnant which have been studied by optical spectroscopy. We observed position 1 of Fesen and Kirshner (1980), and position 31 of D'Odorico (1974). Position 1 of Fesen and Kirshner (1980) is the brightest H-Beta knot they studied, and position 31 of D'Odorico (1974) is one of the densest bright knots in IC443.

Position 1 was readily identified on glass copies of the Palomar Sky Survey plates from the finding charts presented by Fesen and Kirshner (1980), and its position was measured accurately (RA $6^h14^m 32.54^s$ DEC$+22^o$ 54'5.4": epoch 1950). All observations of position 1 were made using this position. The finding chart of D'Odorico (1974) does not allow one to identify the position of knot 31 accurately. An approximate position was measured from the Sky Survey, and then the telescope was moved a beam width in each direction from this point to find the location of maximum emission at 1.644μm (RA 6^h 15^m 17.4^s DEC $+22^o$ 36' 51" : epoch 1950).

The wavelengths of detected lines and associated fluxes are given in Table 1. (Some upper limits for other lines which were not detected are also included).

Observations of Position 1 were made with two different chop amplitudes (170" N-S and 140" N-S). However in both cases there was flux in the southern reference beam, which fell within the remnant. The fluxes quoted for the lines at this position have therefore been derived from the northern part of the nod cycle in which the reference beam falls on blank sky to the north of the optical shell. There is no evidence for flux in the reference beams at position A or 31, and in particular the reference beams for observation of position 31 were chosen so that they were both located on blank sky by using a 100" north-south chop. Figures 2 and 3 show the reduced spectra measured at position 1 and 31. The flux scale for position 1 has been corrected for flux in the reference beam.

Fesen and Kirshner (1980) have derived colour excesses for several different slit positions on IC443 from the ratio of Hα to Hβ. At position 1 E(B-V) = 0.992. This value of reddening along with the reddening law of Rieke & Lebofsky (1985) is used to correct all our observations. Unfortunately there are no extinction measurements for the other positions which we studied, but this value is representative of the reddening found by Fesen & Kirshner (1980) at several other locations on IC443.

III Line identifications

Three different lines are clearly detected in our spectra of IC443. These are at 1.644μm, 2.121μm, and 2.165μm. On the basis of wavelength coincidence the most likely identification for the line at line at 2.165μm is Brackett γ (λ = 2.16550μm). Fesen and Kirshner (1980) measure $I_{H\beta}$ = 2.1 x 10^{-12} erg s^{-1} cm^{-2} (dereddened) in a 2".8 x 40" slit at position 1. Using standard case B recombination theory (Brocklehurst, 1971 and Giles, 1977) and correcting for aperture we expect $I_{B\gamma}$ = 1.5 x 10^{-13} erg s^{-1} cm^{-2} in a filled 19".6 beam. However the emission is not uniform and it is easy to understand why the observed flux at 2.165μm is 1/5 of this.

The line at 2.121μm can be identified as the 1-0 S (1) line of molecular hydrogen. Treffers (1979) has detected the 1-0 S (1) (λ = 2.1218μm) transition of molecular hydrogen in IC443, and Burton *et al.* (1986) have shown that the emission is

extended over many 10's of arc minutes at a flux level almost an order of magnitude brighter than the line detected at position 31. Although this line is found some 8' north of the previous most northerly detection (Burton, private communication 1986) very extended emission at this low level it is not unreasonable, and identification of the line as due to H_2 is reliable.

Several authors have reported line emission near 1.64μm in a variety of different objects - the galaxies M82 and NGC4151, the supernova remnant MSH15-52, and the supernova 1983n (Rieke, Lebofsky, Thompson ,Low, & Tokunaga 1980, Reike and Leboksfy 1981, Seward, Harnden , Murdin, & Clark 1983, Allen, Jones, & Hyland 1985 and Graham , Meikle, Allen, Longmore, & Williams 1986). Searches of line lists and multiplet tables suggest two possible identifications for the line which we have detected at all three positions. The possibilities are [Si I] 1.6459μm and [Fe II] 1.644μm. Both lines are of low excitation and could plausibly be excited in shocks of moderate velocity. Previous authors have identified the emission as the [Fe II] a^4 F-a^4 D line either by using higher resolution to measure the wavelength accurately or by identifying other lines within the same multiplet. However, we also exclude the [Si I] line because if this identification were correct then we would expect another line at 1.6073μm which arises from the same upper level ($3p^2\ ^1D_2$) as the 1.6459μm line and is a factor of 0.35 weaker (for transition probabilities see Mendoza and Zeippen, 1982). On the basis of the flux at 1.6073μm we estimate that the [Si I] line can make no more than ~ 25% contribution to the line at 1.644μm. Furthermore, the ionization potential of Si I is only 8.15 eV, and we might not expect this to be a very abundant species in the cooling region behind the shock where forbidden lines are excited. We will therefore assume that the flux at 1.644μm is due to [Fe II] and that any contribution due to other lines is negligible. A few additional lines appear to be present at the 3-4 sigma level in the 1.6μm spectra of Position 31. The line at 1.681μm can probably be identified as [Fe II]1.677μm.

Table 1

Wavelengths of detected lines and observed and dereddened fluxes

Observed wavelength (μm)	Identification	Observed flux (10^{-14} erg/s/cm^2)	Dereddened Flux (10^{-14} erg/s/cm^2)
Posn. 1*			
2.162	B γ	2.18±0.25	3.01±0.35
1.644	[Fe II]	76.9±1.9	126±3.1
1.600	[Fe II]	<8.7	<17
Posn. A			
2.165	Bγ	1.59±0.14	2.19±0.19
1.644	[Fe II]	35.9±0.60	58.8±0.90
Posn. 31			
2.165	B γ	<0.46	<0.63
2.121	H_2 1-0S(1)	5.13±0.33	7.13±0.46
1.681	[Fe II]	4.51±1.1	7.32±1.8
1.643	[Fe II]	27.3±1.1	44.7±1.8
1.600	[Fe II]	<3.2	<5.3

* Corrected for flux in reference beam.

All errors are 1 sigma, and upper limits are 3 sigma.

IV. Discussion

a) The [Fe II]1.644μm /Bγ ratio

The most prominent feature of these spectra is the [Fe II] line at 1.644μm. Table 2 gives the dereddened ratio [Fe II]1.644μm/Bγ. All these ratios are remarkably large. The [Fe II] line at 1.257μm which arises from the same upper level as the 1.644μm has been detected in the Orion HII region (Lowe Moorhead and Wehlau 1979). They measured a ratio [Fe II] 1.257μm /Hβ = 0.0022, which is consistent with emission from photoionized gas. From this result we can predict the [Fe II]1.644μm /Bγ ratio. The predicted value of [Fe II]1.644μm /1.257μm is just the ratio of the Einstein transition probability multiplied by photon energy, which is 0.70, (Nussbaumer & Storey, private communication 1985). Using standard recombination theory we find that Hβ /Bγ= 37.0, for T_e = 10,000K and n_e = 100cm^{-3}. Thus if conditions of excitation of [Fe II] are similar in IC443 and in the Orion HII region we expect [Fe II]1.644μm/Bγ = 0.057. This is several orders of magnitude smaller than th measured values. Clearly these low excitation [Fe II] lines are much brighter relative to hydrogen recombination lines in this SNR shock than in the Orion HII region. This could be due to more efficient excitation of Fe II relative to hydrogen recombination, or due to reduced depletion of Fe in grains, or most likely a combination of both. In any case it is likely that a high [Fe II] 1.644μm/Bγ ratio is characteristic of shocks, and may conceivably be a useful discriminant between shock and photon excitation.

b) Comparison with shock models and the depletion of iron

The shock models of McKee, Chernoff, and Hollenbach (1984) can be used to predict the ratio [Fe II]1.644μm/Bγ. For a preshock density of 10cm^{-3}, the ratio

Table 2

IR Line ratios

Position	[Fe II]1.644μm/Bγ
A	26.9 ± 2.4
1	41.9 ± 4.9
31	>71 (3 σ)

[Fe II]1.644μm/Bγ is 32 and 69 for shock velocities of 40 and 100 km/s respectively. The optical spectroscopy of Fesen & Kirshner (1980) indicates that shock velocities between 65-100km/s and preshock number densities of 10 - 20 cm^{-3} are consistent with their optical spectra. Thus the observed [Fe II]1.644μm/Bγ ratio is comparable to the calculated values for these conditions and we can confirm that the prominence of the 1.644μm line is due to shock excitation.

These shock models can be used to investigate why the [Fe II]1.644μm/Bγ ratio is so high in shocks. Iron is one of the more highly depleted elements in the interstellar medium, therefore the predicted intensities will be especially sensitive to complex processes such as the modification of the elemental depletions by dust grain sputtering. The iron depletion in Orion is ~ 0.04 relative to Solar abundances (Olthof & Pottasch 1975, Cosmovici, Strafella, and Dirscherl 1980), whereas the shock models described above predict an iron depletion of ~ 0.2 - 0.6 after the shock has passed. Consequently

these models show that the enhanced intensity of the [Fe II] lines relative to hydrogen lines in IC443 is only partially due to grain destruction and the resultant reduced depletion of Fe behind the shock. The dominant effect must be the more efficient excitation of forbidden lines relative to recombination lines in a shock than in a photoionized HII region.

c) Excitation of the [Fe II] lines

Other Fe II lines are present in the spectrum of IC443. These are optical [Fe II] lines of moderately low excitation. Lines of the multiplets a^4F-a^4G, a^6D-a^6S, a^4F-a^4H, and a^4F-a^2G have been detected by Fesen and Kirshner (1980). However no lines of multiplets which might feed the upper state of the 1.644μm line (a^4D), such as a^4D-b^4F or a^4D-b^2P have been detected. These two facts confirm that the excitated states of FeII are populated collisionally. We also note that a comparison of the optical [Fe II] line strengths relative to Hβ in IC443 and in Orion show that these lines are also stronger in IC443. The enhancement is not as great, being between 10 and 40 times brighter.

A good test of whether Fe II levels are populated collisionally is to show that the line ratios, and hence the level population, can be accounted for by a unique temperature (keeping in mind though that in a shock lines are excited at a range of temperatures as gas flowing out of the shock cools). The [Fe II] lines which have been detected arise from upper states with a large range of excitation temperature (a^4D 8000 K, a^4G 16000 K, a^4H 21000 K, a^6S 23000 K, and a^4G 25000 K), and therefore the line ratios should be sensitive to temperature. The optical and IR spectra were measured in different apertures but we can find the ratio of optical lines to the 1.644μm line if we assume that we can find the relative strengths of the [Fe II] lines by using the measurements of hydrogen recombination lines and recombination theory. Iron line ratios have been calculated as in Graham *et al.*. (1986) by considering the detailed balance between excitation and de-excitation. Here the calculation has been enlarged from 16 levels (i.e. up to a^4P) to 43 levels (i.e. up to $b^2P_{1/2}$) so as to include most of the important optical transitions. Einstein A values for transitions within the first 16 levels are from a 7 configuration calculation (Nussbaumer private communication 1985), and the associated collision strengths are from the earlier 4 configuration calculation (Nussbaumer and Storey 1979). For the higher levels A values are from Johansson (1977). Collision

strengths for transitions between the higher levels have not been calculated. An approximate form for the collision strength Ω_{ij} is adopted, $\Omega_{ij} = \omega g_i g_j$. The constant ω is found from the collision strengths which have already been calculated. For Nussbaumer and Storey's (1979) calculation the mean value $< \Omega_{ij}/g_i g_j > = 0.02$. Most of these values lie in the range 0.01-0.04 and so adopting $\omega = 0.02$ probably gives the collision strength to a factor of 2. The non detection of the [Fe II] 1.600μm line indicates that the [Fe II] lines are excited under conditions of low density. The limits indicate that $n_e < 2x10\ 4 cm^{-3}$ (3 σ). Furthermore, [S II] line ratios of Fesen and Kirshner (1980) show that the electron density is ~100-500 cm^{-3}. Under these conditions the level population is far from local thermodynamic equilibrium and the line ratios are particularly sensitive to the adopted collision strengths. From the scatter in the calculated collision strengths about the adopted form, we can probably only predict the line ratios to a factor of 2, and hence calculate temperatures to ~1000K.

The optical to IR line ratios for position 1 are given in Table 3, along with the temperture inferred from this ratio. The errors quoted reflect uncertainty in the atomic data.

The mean temperature derived from the [Fe II] line ratios in Table 3, 5100K, is significantly lower than that inferred from [O III] (25000K), [N II], [S II], or [O II] (11000K) by Fesen and Kirshner 1980. This is not surprising since the ionization potential of Fe II is 7.1eV less than the lowest ionization potential optical diagnostic ([SII]). The [Fe II] lines must be excited downstream of the N, O, and S lines where the gas is cooler and the degree of ionization is lower.

There is a significant trend for the temperature derived from different [Fe II] lines to correlate with the excitation energy of the upper level of the line. A range of temperature must exist in the Fe II ionization zone corresponding to the range given in Table 3. At first sight it may be surprising that the temperature derived from some of the lower excitation [Fe II] lines indicates that these lines are excited where hydrogen has recombined (T ~< 5000K). Shock models predicting [Fe II] 1.257μm line intensities have been reported by McKee Chernoff and Holenbach (1984). Some emission from Fe

II is excited in the hydrogen recombination zone (T > 5000K), but, depending upon conditions, there can be substantial emission in predominantly neutral gas. Ionization of ions such as Fe II is maintained by UV photons penetrating far downstream from the hot postshock gas where they were emitted.

Clearly these [Fe II] lines are probing cooler and consequently denser gas than is usually studied by more traditional diagnostic lines of N, O, and S. This suggests not only that IR [Fe II] line spectroscopy might be useful as a diagnostic for detecting shocked gas in regions of high extinction, but that it may also be valuable in the study of slow shocks where N, O, and, S lines are not excited. This will be especially true of the infrared lines such as at 1.644μm.

d) Molecular Hydrogen

The vibrationally excited H2 detected at position 31 could be produced by inelastic collisions with atoms or molecules or by near-ultraviolet pumping in the electronically excited Lyman and Werner bands followed by a radiative cascade which populates the excited vibrational and rotational levels of the ground electronic state. The ratios of H_2 lines from different vibrational upper states measured by Burton *et al.* (1986) indicate that the H_2 is excited collisionally in shocks. Although we do not have measurements of line ratios to allow us to establish the nature of the excitation it seems reasonable to assume that the same mechanism is at work here on the eastern edge of the remnant as is found at further south at the H_2 peak.

The detection of [Fe II] and the 1-0 S(1) line of H_2 in the same aperture at position 31 is noteworthy because rather different physical conditions are required to produce these lines. The ionization potential of Fe I is 7.87eV and the dissociation energy of H_2 is 4.48 eV. Therefore Fe II and H_2 cannot coexist in substantial quantities. As the observed emission arises from the very edge of the remnant it seems unlikely that the [Fe II] and H_2 lines arise from two distant regions along the same line of sight. Therefore, the emitting regions are probably separated by a distance less than or comparable to the projected diameter of the aperture on IC443. At a distance of 1.5kpc the 19.6" aperture corresponds to 0.14pc. It is possible that the observed emission arises from the SNR shock propagating into two adjacent regions of different density. Alternatively molecules must form down stream of the ionized gas where the [Fe II] lines

Table 3

Line intensities relative to Hβ and [Fe II]1.644μm, and inferred temperatures.

Upper state	Energy (cm-1)	Line (Å)	I Hβ*	I [Fe II]1.644μm	Temperature (K)
a^4G	25428.0	4244	4.5	4.1	5200 ± 800
a^6S	23317.6	4287	4.5	4.1	6600 ± 1200
	"	4359	4.0	3.6	7100 ± 1200
	"	4413	1.8	1.6	6200 ± 1200
a^4G	21251.6	5158	6.7	6.1	4200 ± 600
	21430.4	5261	2.6	2.4	3900 ± 500
a^2G	15844.7	7155	3.7	3.4	2800 ± 500
a^4D	7955.3	16440	110	100	...

* H beta = 100

Ratios are corrected for reddening, E(B-V)=0.992, as described in the text.

are excited. Inspection of interference filter plates of IC443 (Fesen & Kirshner 1980) indicates that there is a wealth of structure on scales of 15" - 30", suggesting that our 19.6" aperture is admitting emission from regions with very different conditions.

V. Conclusions

We have detected the 1.644μm [Fe II] line at several positions in the supernova remnant IC443. The line is typically 30 times brighter than Bγ and consequently comparable in strength to Hβ. This line ratio is substantially different from that expected in an HII region and appears to be a result of collisional excitation and grain destruction in a shock. Consequently the [Fe II]1.644μm/Bγ ratio is a powerful discriminant between shock excited and photoionized gas.

The [Fe II] emission is excited in gas which is cooler than that which gives rise to optical emission lines. Therefore [Fe II] 1.644μm emission might be useful for tracing intermediate velocity shocks (30-60km/s) where optical lines are weak. Furthermore the extinction at 1.6μm is only 1/5 of that found in the visible and so this line could be used to trace shock activity in dense regions where the extinction is high.

The [Fe II] 1.644μm and H_2 2.121μm lines have been detected in the same aperture. At the present spatial resolution it is impossible to determine whether the emission arises from the same postshock flow or from two distinct regions. However, if future studies show that Fe II ions and H_2 molecules are present in a single shock then the diagnostic utility of [Fe II] lines can be brought to bear on the problem of H_2 destruction, formation and excitation in shocks.

This work was carried out while J.R.G. was a visiting astronomer at the Royal Observatory Edinburgh, which also operates the United Kingdom Infrared Telescope on behalf of the U.K. Science and Engineering Research Council. We are indebted to Peter Meikle who kindly agreed to let us carry out the exploratory observations which were made in 1985. It is also a pleasure to acknowledge the enthusiasm and interest of Bob

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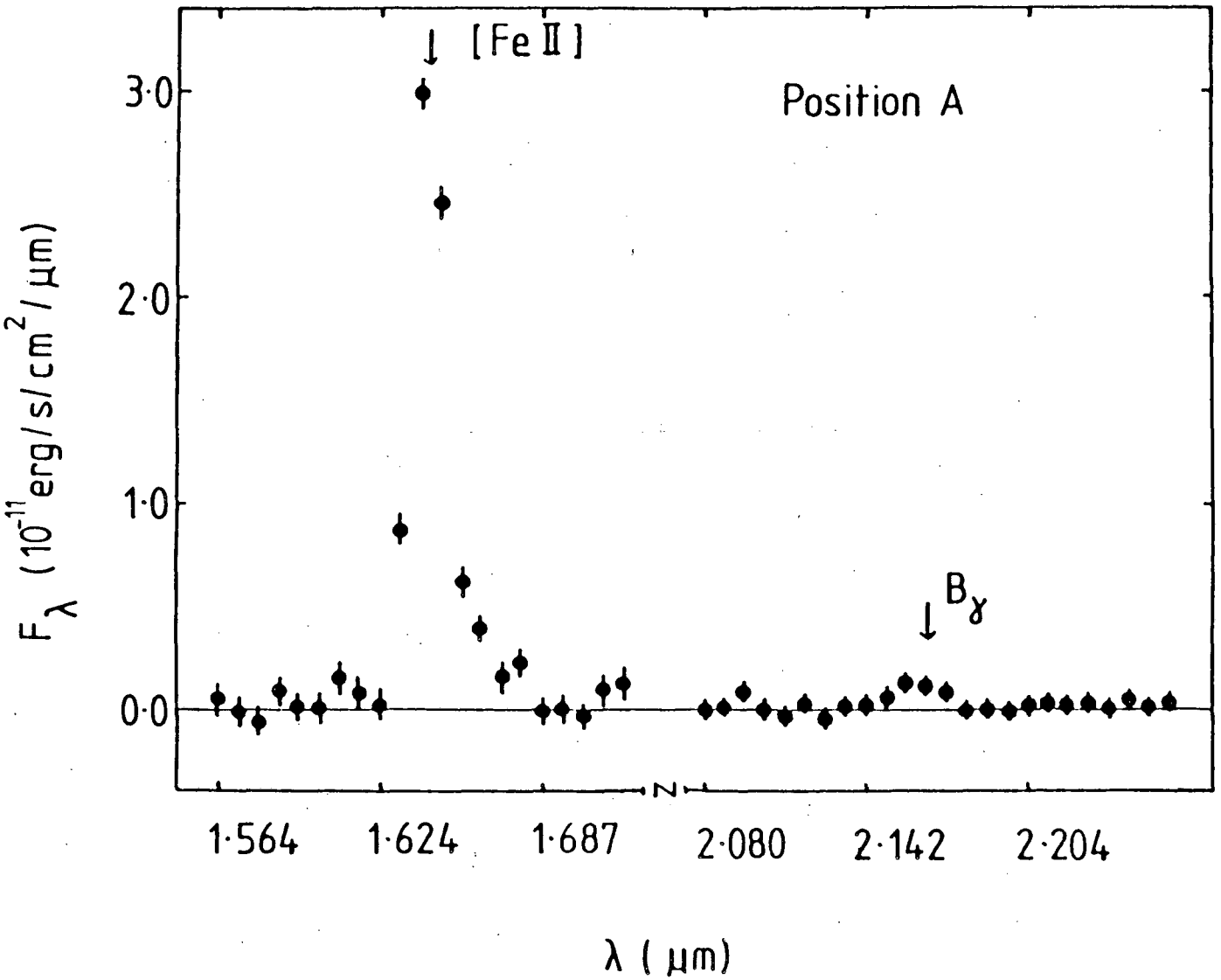

Figure 1. The infared spectrum of IC443 at position A. The wavelengths of [Fe II]1.644μm and Bγ are indicated by arrows. Note that the wavelength axis is not continuous.

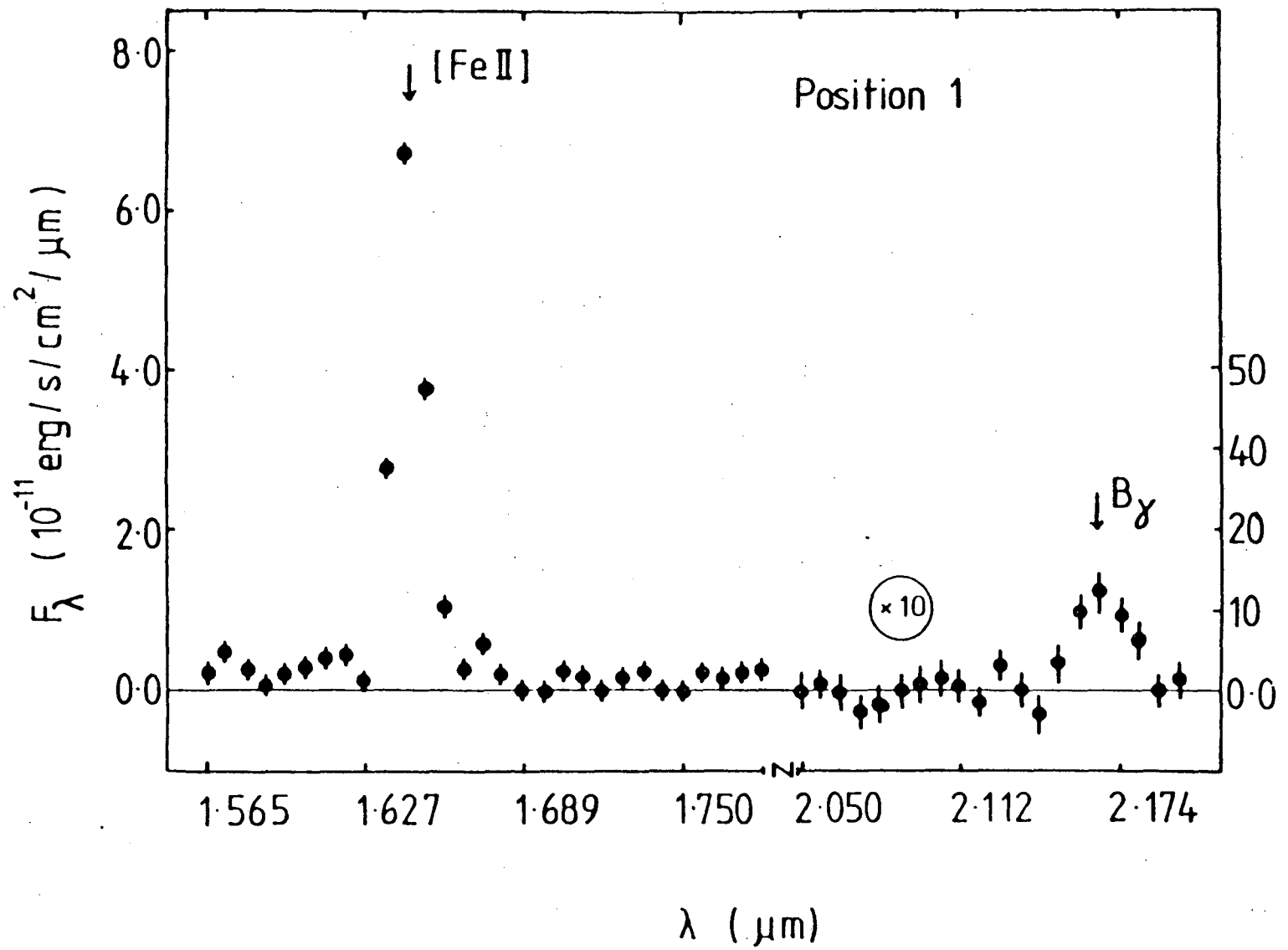

Figure 2. The infrared spectrum of IC443 at position 1. The 2μm spectrum has been multiplied by 10 to emphasise Bγ. The wavelengths of [Fe II]1.644μm and Bγ are indicated by arrows. Note that the wavelength axis is not continuous.

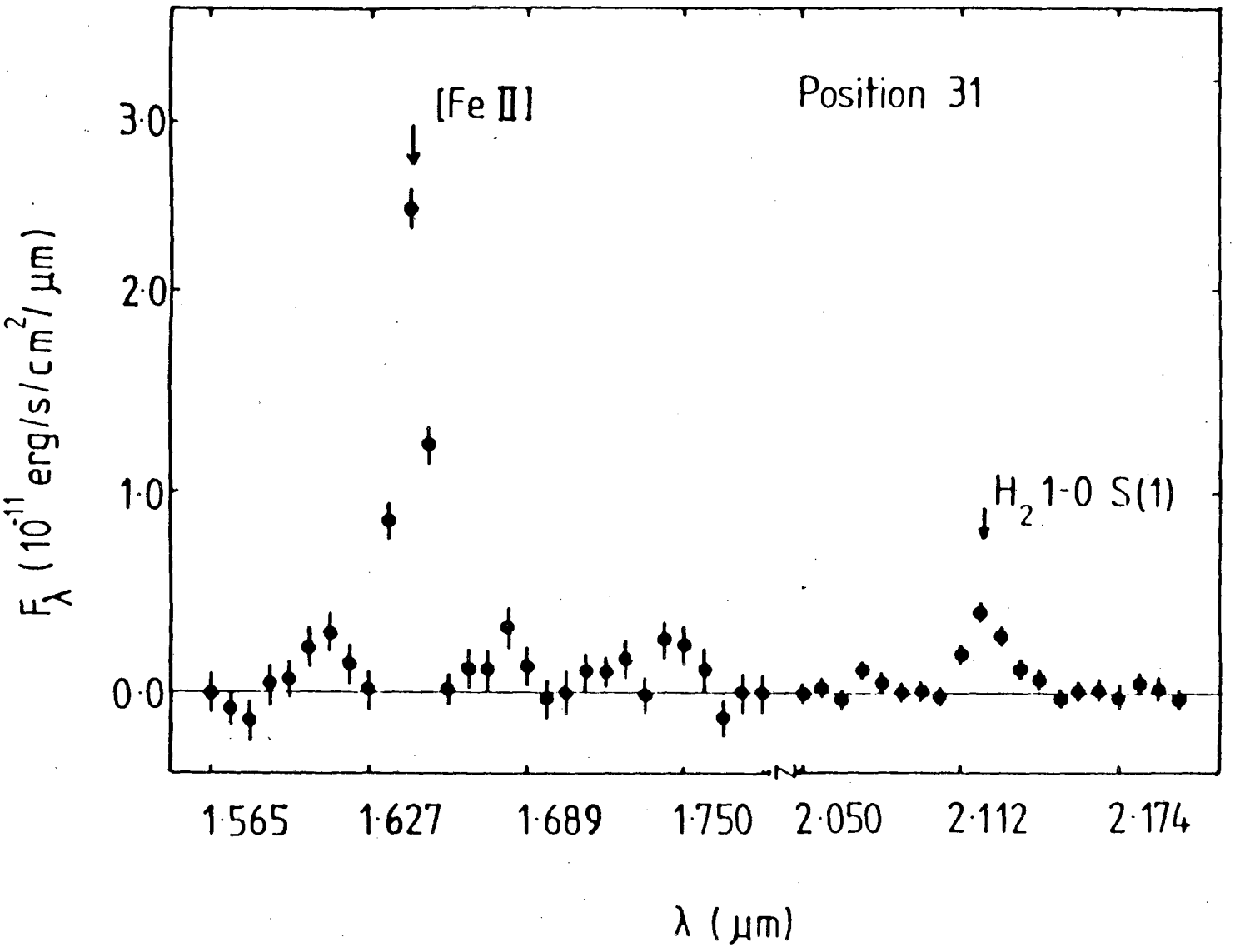

Figure 3. The infared spectrum of IC443 at position 31. The wavelengths of [Fe II]1.644μm and H_2 1-0 S(1) are indicated by arrows. Note that the wavelength axis is not continuous.

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LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720