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EXTRAGALACTIC INFRARED SPECTROSCOPY

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ABSTRACT

We are engaged in a programme to explore the spectra of galaxies in the near-infrared (H & K) atmospheric transmission windows. We have detected emission lines due to molecular hydrogen, atomic hydrogen recombination lines, a line we attribute to [FeII], and a broad CO absorption feature. Lines due to H_2 and [FeII] are especially strong in interacting and merging galaxies, but we have also detected them in Seyferts and 'normal' spirals. These lines appear to be shock-excited. Multi-aperture measurements show that they emanate from regions as large as 15 kpc. We argue that starbursts provide the most plausible and consistent model for the excitation of these lines, but the changes of relative line intensity of various species with aperture suggests that other excitation mechanisms are also operating in the outer regions of these galaxies.

1. INTRODUCTION

Spectroscopy in the near-infrared atmospheric windows is an almost completely undeveloped tool for investigating physical processes in galaxies. Until recently there have been only two detections of H_2 in galaxies, in N1068 (Thompson, Lebofsky & Rieke 1978) and N3690-IC694 (Fischer, Simon, Benson & Solomon 1983). There have also been only two detections of the 1.644 μm lines which are attributed to [FeII] in the nuclei of galaxies, in M82 (Rieke, Lebofsky, Thompson, Low, & Tokunaga 1980) and in N4151 (Rieke & Lebofsky 1981). There have been a few more detections of H Brackett lines in galaxies, but in total probably less than ten (cf. Beck, Beckwith & Gatley 1984).

We have embarked on a programme to explore the spectra of several classes of galaxies in the H & K atmospheric windows. Our interest in attempting such spectroscopy arose from our studies of interacting and merging galaxies (Joseph, Meikle, Robertson & Wright 1984, Wright, Joseph & Meikle 1984, Graham, Wright, Meikle, Joseph & Bode 1984, Joseph & Wright 1985). The collision of two gas-rich galaxies must be one of the most likely places in the universe to look for shock-excited H_2, and we hoped to be able to use these lines as shock diagnostics and independent indication of a genuine physical interaction. This conjecture was supported by the discovery of strong H_2 emission in the interacting galaxies N3690-IC694 by Fischer et al. (1983), and subsequently by our discovery (Joseph, Wright & Wade 1984) and others' (Becklin, DePoy & Wynn-Williams 1984, Rieke et al, 1985) of extraordinarily luminous H_2 emission in two of the most intriguing 'IRAS galaxies,' N6240 and Arp220. We have extended this observing programme to include other classes of galaxies, partly for comparison purposes, but chiefly as a systematic exploration of the near-IR spectroscopic properties of spiral galaxies in general.

2. OBSERVATIONS

Our observations have been obtained at UKIRT, using a circular variable filter spectrometer. This instrument provides a spectral resolution $\lambda/d\lambda \sim 120$, or about 2500 km/sec. Since the instrument employs re-imaging optics, this resolution is independent of aperture. Our approach has been to begin study of a given galaxy using the 19.6 arcsec aperture, and then to obtain spectra at successively smaller apertures. In one or two nearby galaxies we have also measured spectra in several different positions not centred on the nucleus. So far we have obtained complete spectra in the H & K windows for about 15 galaxies. Most of these are interacting and merging galaxies, but we have good spectra for four nearby bright spirals and two Seyfert galaxies.

The features which appear most frequently in these spectra are the quadrupole vibration-rotation lines of H_2, H recombination lines in the Brackett series, a line at 1.644 μm which we tentatively attribute to [FeII], and the stellar absorption feature due to CO. Examples of the spectra we measure are shown in Figs. 1 - 4. These spectra have been ratioed with the spectrum of a G-type star taken at similar airmass to remove effects of the atmosphere and instrumental response. The spectra illustrate how useful it is to work at the high altitude of UKIRT on Mauna Kea. For example, one can study the 1-0 Q-branch of H_2 in galaxies even at redshifts as large as that of N6240 (7500 km/sec).

3. RESULTS

We have done preliminary reduction of the spectra for a subsample of the galaxies so far observed to obtain fluxes for the H_2, Brackett γ, and [FeII] lines. In the following we summarise the physical parameters that characterise this data, and the apparent trends which seem to be emerging.

3.1 Excitation mechanisms

Both shocks and fluorescence following absorption of a UV photon in the Lyman or Werner bands have been suggested for the H_2 excitation. The evidence from relative line intensities in the data available so far is consistent with shock excitation. Table I shows relative line intensities expected for excitation by a 10 km/sec shock and for UV fluorescence. For comparison we give the relative intensities of several of the H_2 lines for N6240 and Arp220. The most critical indication is probably the intensity of the 2-1 S(1) line relative to that of the 1-0 S(1) line. The data for these two galaxies is clearly consistent with shock excitation and incompatible with the UV fluorescence model. We have also looked hard for the 2-1 S(1) line as evidence of UV fluorescence in the Seyfert galaxies we have observed. The line intensities favour collisional excitation in these galaxies as well. However, we intend to obtain spectra in still smaller apertures to distinguish the features of the active nucleus itself more clearly.

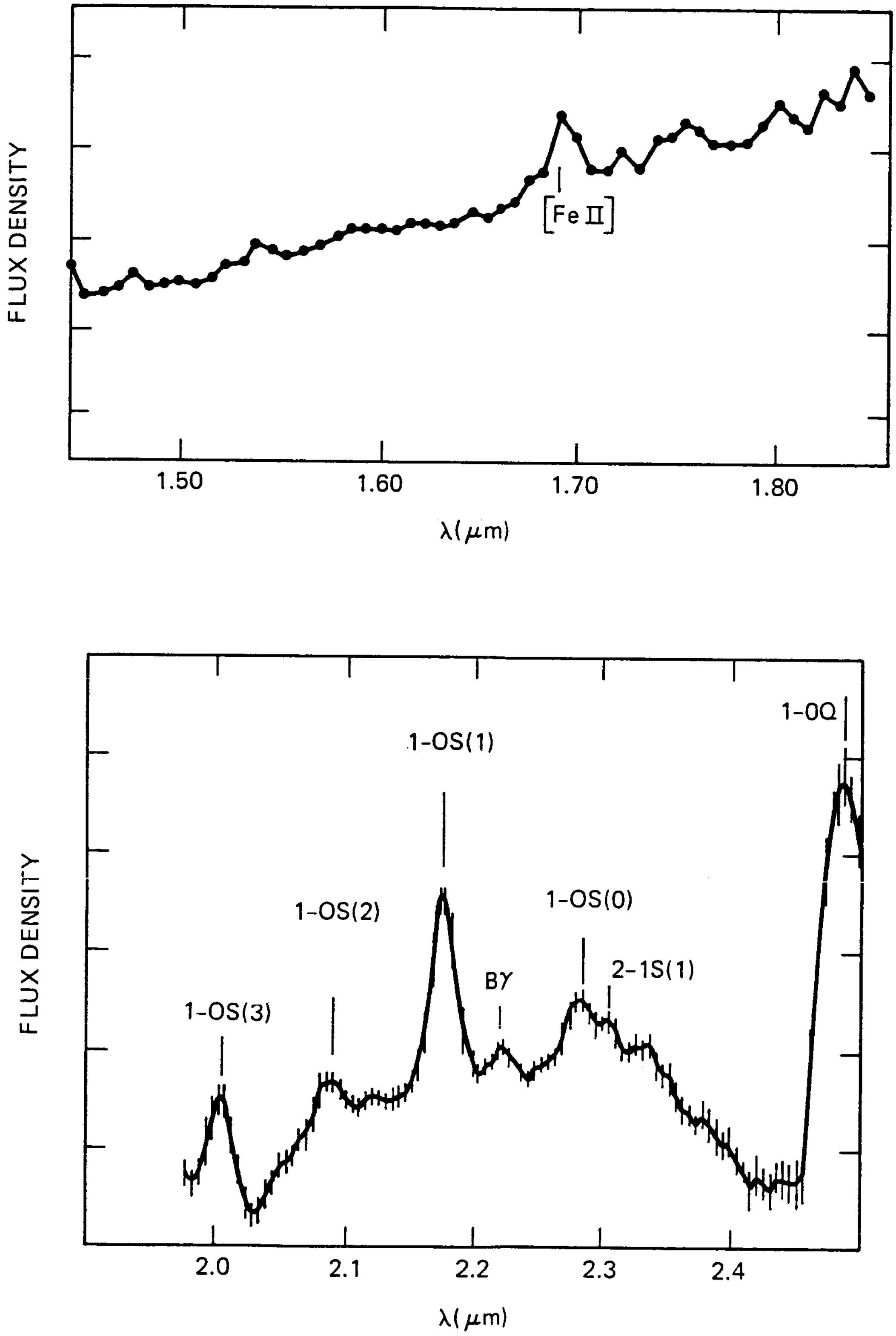

Figure 1. Spectra of the merging galaxy N6240 in a 19.6 arcsec aperture.

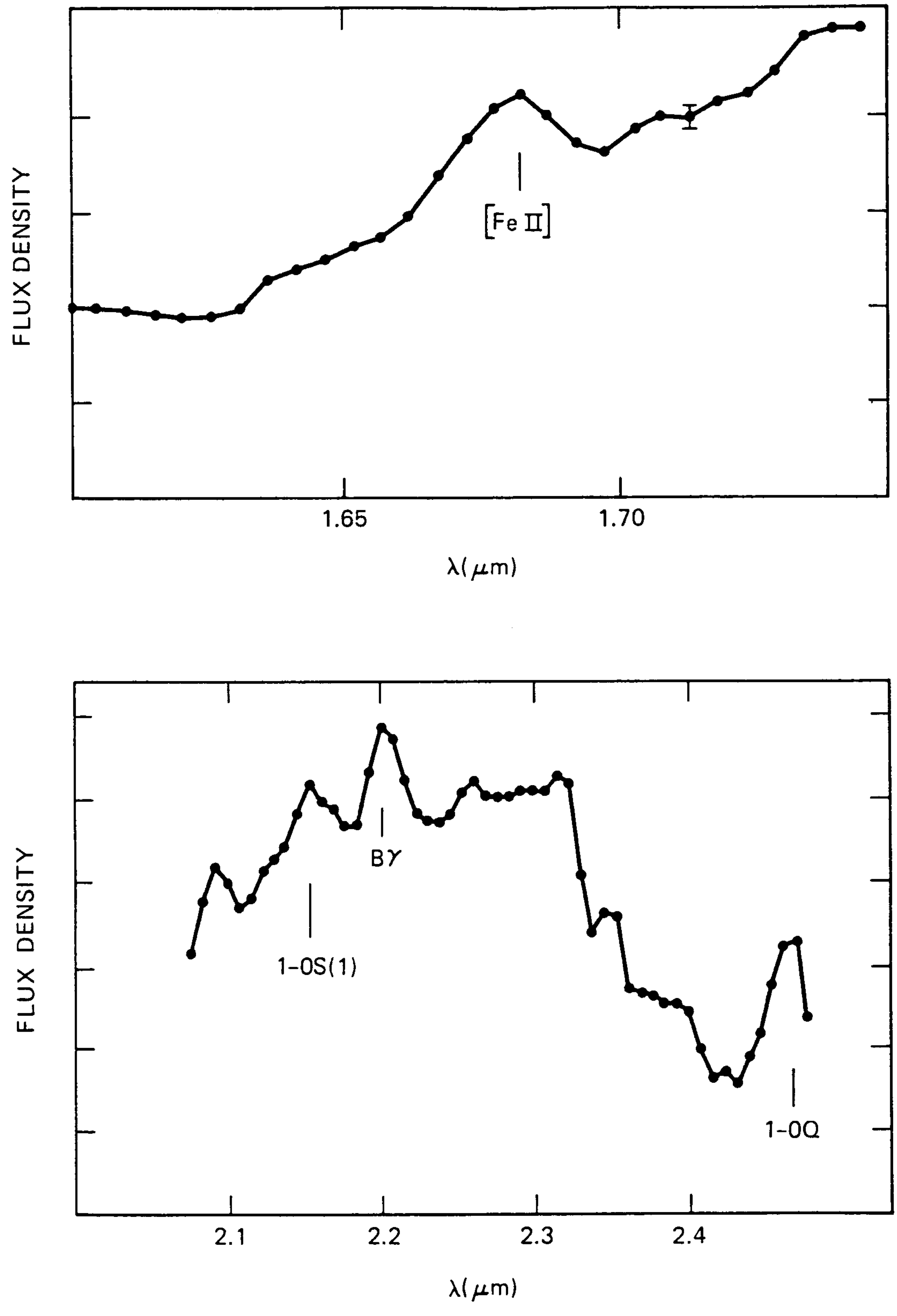

Figure 2. Spectra of the merging galaxy N1614 in a 19.6 arcsec aperture.

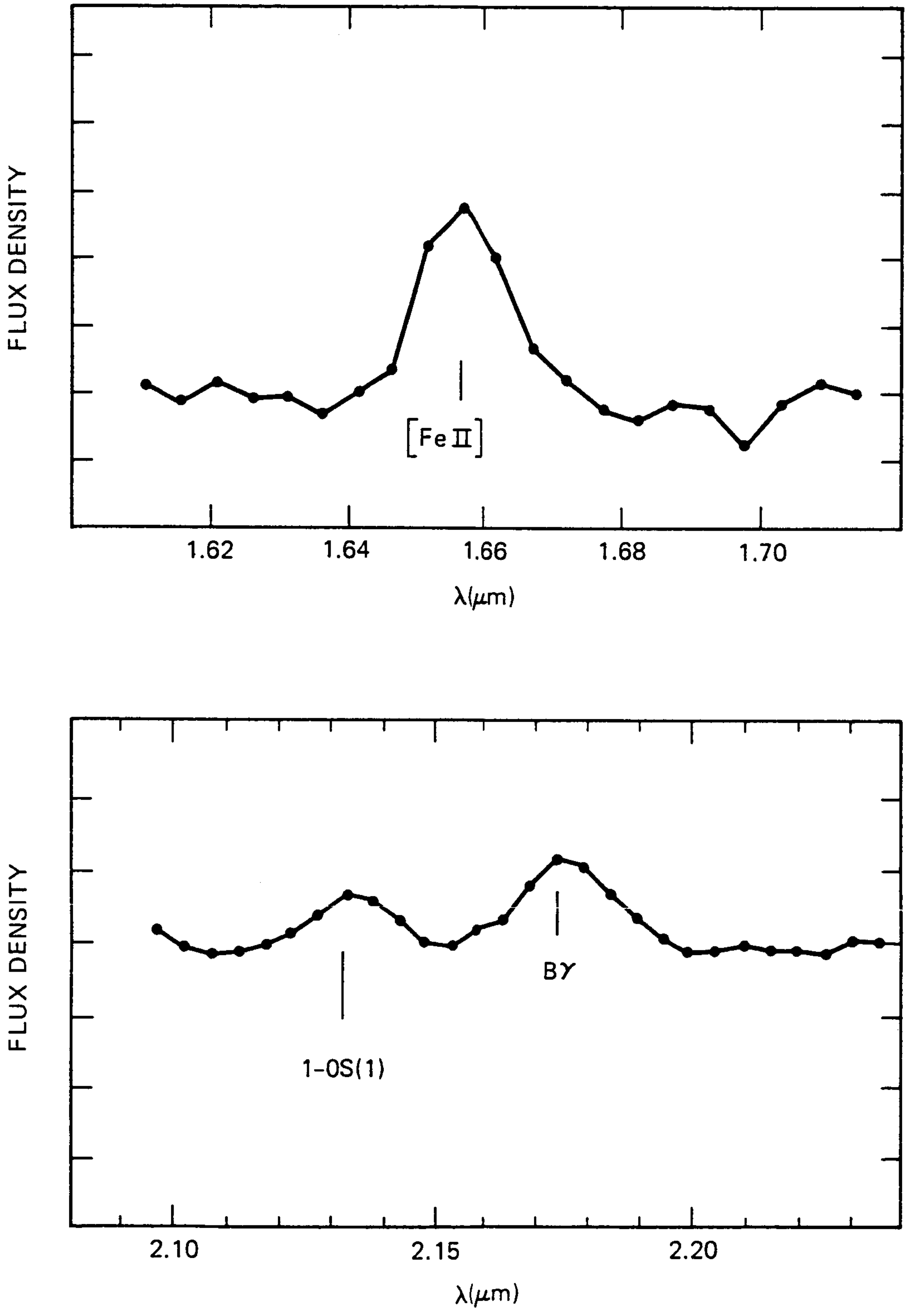

Figure 3. Spectra of the merging galaxy N3690A in a 19.6 arcsec aperture.

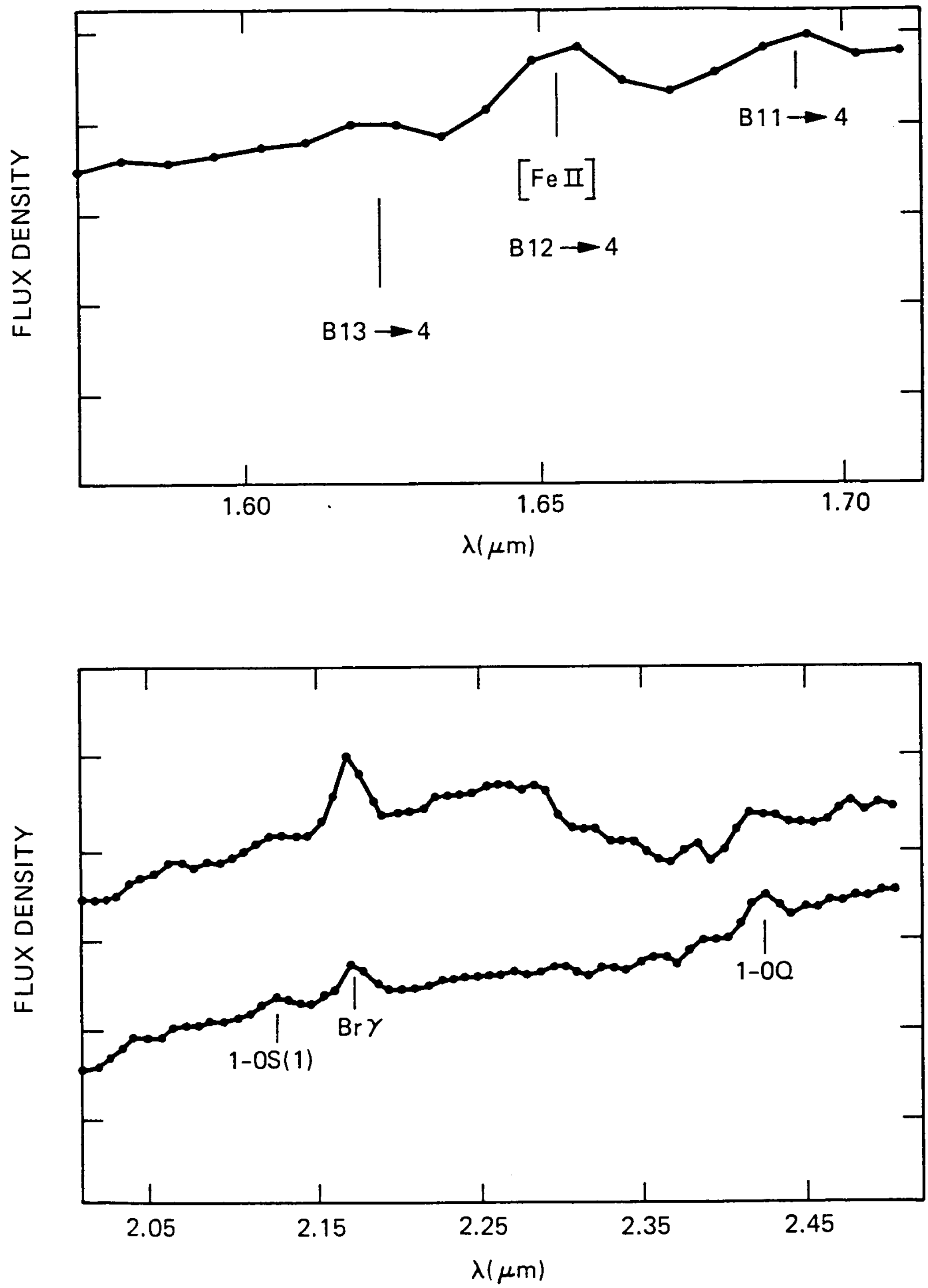

Figure 4. Spectra of N253 in a 19.6 arcsec aperture. The upper K window spectrum has been ratioed by the spectrum of an A-type star, which gives spuriously enhanced Brackett γ. The spectrum just below has been ratioed with the spectrum of a star with a very large CO index to remove the CO feature in the galaxy spectrum and show the Q-branch more clearly.

TABLE I. RELATIVE LINE INTENSITIES FOR H_2 EXCITATION

Line	N6240	Arp220	Shock*	UV†
1-0 S(0)	0.28	0.17	0.22	0.67
1-0 S(1)	1.0	1.0	1.0	1.0
1-0 S(2)	0.24		0.36	
1-0 S(3)	0.77		0.95	
1-0 Q(1-7)	2.2	4.5	2.4	2.7
2-1 S(1)	0.14	0.05	0.1	0.55

*Hollenbach & Shull (1977)
†Black & Dalgarno (1976)

The 1.644 μm [FeII] line is also collisionally-excited. If the [FeII] were emitted from an HII region, one would expect the ratio of the [FeII] λ1.644 μm line to Brackett γ λ2.166 μm to be ~ 0.06 (Graham, Wright & Longmore 1986). We find this ratio typically to be at least 10 times larger, suggesting that the line is not excited by photoionisation in an HII region. It is very difficult to excite this line by UV fluorescence, and we do not observe a line at 2.09 μm which we would expect to see if the relevant terms were populated by this mechanism. The line is therefore almost certainly shock-excited.

This is an important result. Shock speeds in excess of 30 km/sec are required to excite the [FeII] emission, whereas shock speeds as low as 5 km/sec can excite the H_2 1-0 S(1) line. Thus these lines provide powerful shock diagnostics. For example, their relative spatial extent can constrain the kinds of astrophysical source(s) driving the shocks. Comparison of these indicators with the extent of Brackett γ and infrared continuum maps should then provide rather detailed insight into the astrophysics associated with the nuclear infrared activity in these galaxies.

3.2 Luminosities in H_2 emission lines

The luminosities of the 1-0 S(1) emission lines discovered in 1984 in N6240 and Arp220 are astonishingly large, ~ 10^8 and 10^7 L⊙ respectively. How do these luminosities compare with those for a larger sample including other types of galaxies? The samples are still small, but some trends may be appearing. Table II presents the 1-0 S(1) luminosities (H_0 = 50 km sec^{-1} Mpc^{-1}) for the line fluxes obtained in a 19.6 arcsec aperture centred on the nucleus of each galaxy.

These luminosities are enormous! At the upper end they compare with the 10 μm continuum luminosities of starburst galaxies. Another way to appreciate the physical significance of these luminosities is to ask what masses of H_2 must be shock-excited to produce these luminosities. If the temperature is ~ 2000 K, these luminosities imply masses of excited H_2 of 10^2 to 10^5 M⊙, and excitation rates of 30 to 30,000 M⊙ of H_2 per year. The timescales of the processes producing this excitation must be large, since we have detected H_2 emission in virtually every interacting or merging galaxy we have observed, and in most other galaxies as well. If the excitation were a starburst, one expects a lifetime of $\gtrsim 3 \times 10^7$ years, whereas if it were due to spiral density waves or to gas flows

TABLE II. LUMINOSITIES IN THE H_2 1-0 S(1) LINE

Galaxy type	Luminosity range (L⊙)
Mergers	$3 \times 10^6 - 3 \times 10^8$
Interacting (not merging)	$2 \times 10^5 - 1 \times 10^7$
Starburst (N253)	$\sim 7 \times 10^4$

induced by bar instabilities the lifetime would be ~ 10^{10} years. Multiplying these timescales by the excitation rates we have inferred suggests that all the molecular gas must be excited over the lifetime of the starburst in N253. In the mergers, the result is even more striking: every H_2 molecule must be excited many times, in order to account for the high excitation rates we find in these systems.

3.3 Energy source driving these shocks

Because many of these galaxies are ultra-luminous IR sources, it might be expected that radiation pressure would be sufficient to drive the shocks we infer are present. However, the radiation pressure, L_{IR}/c, is << $\dot{m}v_s$ for the excitation rates given above, even for shock velocities v_s as low as 10 km/sec.

Alternatively, it may be that the relative kinetic energy of the collisions for the interacting and merging galaxies, or mass outflows from star formation regions or from the active nucleus in the case of the Seyferts, are the underlying energy sources driving the shocks. To investigate these possibilities we have compared the ratio of the luminosity in the 1-0 S(1) line to the total IR luminosity. This ratio should have a characteristic value for star formation regions, since the S(1) line luminosity is a measure of the mechanical energy in the outflow from a star formation region and the IR luminosity is a measure of the total energy of the starburst. The ratio is 1×10^{-5} for Orion (Shull & Beckwith 1982). For all the galaxies we have observed this ratio does not deviate above or below 1×10^{-5} by more than a factor of ~ 2, with one notable exception. For N6240 this ratio is at least 15 times larger. Our inference then is that mass outflows from star formation regions similar to Orion can account for the excitation of H_2 in all these galaxies, except for N6240, and in this case it is likely that the relative kinetic energy of the merger has produced the higher excitation rate we observe.

3.4 Spatial extent of the line emission

We have not yet completed our multi-aperture spectroscopy for this galaxy sample, but the data available for galaxies observed in more than one aperture suggests that the line emission has considerable spatial extent. In Table III we list the relative line intensities found in various apertures, with the corresponding linear dimensions associated with these apertures, for several galaxies. The most noteworthy feature is the large extent of the H_2 and [FeII] emission, over much of the disc, in the two merging galaxies N6240 and N1614. There is spatial extent of at least 2 or 3 kpc for the H_2 emission in the Seyfert galaxy N3227 and in the interacting galaxy N2798. Although the Brackett γ is also spatially extended, it appears to be more centrally condensed in the latter two galaxies than is the H_2 emission. We emphasise that even these results on spatial extent are lower limits--19.6 arcsec is simply the largest aperture available in our spectrometer.

TABLE III. SPATIAL EXTENT OF LINE EMISSION

Galaxy	Line	Aperture				Linear scale
		5"	8"	12"	20"	for 20"
N6240	1-0 S(1)	1.0	1.5	2.1	2.6	14 kpc
	[FeII]	1.0	1.3	1.6	1.8	
N1614	[FeII]		1.0	2.0	3.0	9 kpc
N3227	1-0 S(1)		1.0		2.1	2 kpc
	S(1)/Bγ		1.0		1.3	
N2798	1-0 S(1)			1.0	2.3	3 kpc
	S(1)/Bγ			1.0	2.0	
N253	See text					

We have the most detailed information on the nearby starburst galaxy N253. Here we have achieved some spectral mapping. We find the H_2 emission extended to at least ± 20 arcsec, i.e. ± 300 pc, along the major axis. By contrast the [FeII] and Brackett γ emission are much more centrally condensed, and seem to follow the 10 μm emission mapped by Rieke & Low (1975).

4. STEPS TOWARD AN INTERPRETATION

There are several plausible mechanisms which might be responsible for the shock excitation we observe in these galaxies. (1) Mass outflows associated with starbursts have already been mentioned, and are one of the sources of H_2 excitation in our own galaxy. (2) Dynamical processes associated with the collision between two galaxies, as discussed by Martin Harwit elsewhere in this volume, are also a likely source of shock excitation. (3) Mass outflows associated with Seyfert nuclei may be responsible for shocks in the vicinity of the nucleus in this class of galaxies. (4) Shocks due to spiral density waves or due to flows associated with bar instabilities may also be a source of excitation. In the following we will use the results outlined above to work toward a consistent picture of the astrophysical processes which might account for the line emission seen in these galaxies.

Firstly, which of the above processes can be responsible for the greatly extended H_2 emission? In N253, the [FeII] emission does not show similar spatial extent, and so the slower shock speeds characteristic of spiral density waves, or shocks associated with the bar in this galaxy are reasonable. The fact that Brackett γ is centrally condensed in this galaxy also suggests that outflow from star formation regions is not likely to be responsible for the extended H_2 emission in N253.

For the merging galaxies, the [FeII] emission seems to be as spatially extended as the H_2. Since the [FeII] requires rather fast shock velocities, gentler processes such as spiral density waves are not so likely to dominate the excitation. In this case either star formation or the energy of the interaction is likely to be responsible. If it were star formation, we would expect the outflows from massive young stars to be responsible for exciting the H_2, and outflows from supernova remnants to provide the fast shocks needed to excite the [FeII]. The strong emission from [FeII] in the 1.644 μm line in the supernova remnant IC443 (cf. Graham, Wright, & Longmore 1986) must be an archetypal example of this process.

Secondly, the approximate constancy of the ratio of S(1) line to total IR luminosity for nearly all galaxies helps to distinguish the relative importance of these processes. The constancy of this ratio from one merging galaxy to another might be understood in terms of the mechanical energy of the collision, but it is difficult to see why, in this case, it would be the same for non-merging interacting galaxies, a Seyfert, and a starburst galaxy. Moreover, that this ratio is quantitatively the same as that for a local star formation region (Orion) is strongly suggestive that, in general, the H_2 is excited by mass outflows from star formation regions in the central regions of these galaxies. N6240 is clearly the exception, and as we suggested some time ago (Joseph et al. 1984), it is likely that the relative kinetic energy of the interaction dominates the H_2 excitation in this merger.

If we adopt this interpretation, we can ask whether it is consistent with other information available for these galaxies. One of the most important questions is whether the H recombination line luminosity is consistent with a starburst model. In our original paper on H_2 emission in N6240 and Arp220 (Joseph et al. 1984) we called attention to an apparently low flux of Lyman continuum photons as evidenced by our failure to detect Paschen α at a similar sensitivity as that used when we first detected H_2. This point has been pursued by Becklin et al. (1986), who have detected the Paschen α line in a 5 arcsec aperture, and used the ratio of the luminosity in this line to the total IRAS luminosity as a major argument to support their suggestion that N6240 is not powered by a starburst at all, but by a quasar-like active nucleus. To investigate this point further we have calculated the ratio of the Brackett γ flux we have measured in a 19.6 arcsec aperture to the IRAS 25 μm flux for these galaxies, including N6240. We take the flux at 25 μm to indicate the starburst component of the far-IR emission, as the spectral synthesis models show is reasonable (cf. Helou et al. in this volume). Therefore, the Brackett γ/25 μm flux ratio should be roughly constant for galaxies powered by a starburst. The ratio, shown in Table IV, is remarkably constant, especially considering the rather heterogeneous collection of objects, and the fact that it will be somewhat sensitive to reddening. Clearly, on this criterion, N6240 is not weak in H recombination line strength among the galaxies measured. On the other hand, Arp220 may be a bit short of Brackett γ photons.

TABLE IV. RATIOS OF BRACKETT γ TO 25 μm FLUX

Galaxy	Bγ/25 μm ($x10^5$)
N6240	12
Arp220	1.7
N3256	3.9
N2623	4.6
N1614	6.6
N3227	6.2
N2798	7.4
N253	3.0

Finally we can use our spectroscopic data to infer what supernova rate is implied if the [FeII] emission is due to supernovae associated with the starbursts. Graham, Wright & Longmore (1986) have discovered the 1.644 μm [FeII] line in the galactic supernova remnant IC443. The lifetime and [FeII] luminosity of this supernova remnant, and the [FeII] luminosities of the galaxies in the present sample indicate a supernova rate of < 1 per year for the interacting and Seyfert galaxies, and 10 - 70 supernovae per year in the mergers. These are not unreasonable supernova rates.

However, the fact that the relative strength of the S(1) line flux to the Brackett γ flux seems to be changing with aperture, for some of the galaxies studied so far, as shown in Table III, suggests that starbursts alone may not be enough to account for all the excitation of H_2. It will be particularly germane to find out how the [FeII]/Bγ ratio varies with aperture to see how well the starburst picture holds up for the excitation well outside the central regions of activity in these galaxies.

5. SUMMARY AND CONCLUSIONS

We have measured near-IR emission lines due to H_2, Brackett γ, and [FeII] for a variety of classes of galaxies. The lines due to H_2 and [FeII] are especially strong in interacting and merging galaxies. Multi-aperture measurements show that the emission is generally extended over kiloparsec scales. The H_2 and [FeII] emission is apparently excited by shocks, in which case the latter requires shock velocities > 30 km/sec. Consideration of several processes which might produce emission lines from these three species shows that, in general, starbursts provide the most attractive and consistent model. In particular, the ratio of the H_2 flux to the total IR flux, the ratio of the Brackett γ flux to the 25 μm flux, and the luminosities of the [FeII] provide semi-quantitative support for this interpretation. However, starbursts cannot be the whole story for in some cases the ratio of H_2 to Brackett γ emission shows a marked increase with aperture, suggesting that shocks due to spiral density waves or to the interactions may become important outside the most active central regions in these galaxies.

More quantitative and detailed presentations of the IR spectroscopic data for these are other galaxies we have observed will soon be submitted for publication in Monthly Notices of the Royal Astronomical Society.

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DISCUSSION

SHULL:

The supernova shocks would be expected to destroy the H_2 at velocities above 25 km s^{-1}. Can you discuss this difficulty in your model of star formation excitation of the 2μm H_2 emission?

(Note, added afterwards: The Hollenbach-McKee idea of reforming H_2 behind the shock (by grains that survive shock destruction) may not work here, since the gas will have cooled well below 1000 K so that vibrational lines cannot be excited.)

JOSEPH:

There are shocks of three different origins in the model outlined: 1) those due to the galaxy-galaxy collision, 2) those due to outflow from star formation regions, and 3) those associated with supernovae. The Hollenbach-McKee idea of reforming H_2 on grains that survive the shock applies to the first case. We are probably seeing excitation mainly because of the second case for the H_2, and mainly because of the third case for the [FeII]. Of course, the localized regions emitting the H_2 are not the same as those emitting the [FeII], but they both emanate from the same general volume. There are examples in the Galaxy in which one sees both [FeII] and H_2 emission, for example, in the supernova remnant IC443.

BURBIDGE:
Can you say anything about the Fe/H ratio in these objects. Is the ratio normal?

JOSEPH:
I don't think these measurements permit us to deduce much about the total Fe/H abundance ratio.

TELESCO:
1) How did you determine that the H_2 is extended in these sources?
2) Do you know the ratio of [FeII]/L_{IR} for the Seyfert NGC 4151 and how does it compare to the values for this sample?

JOSEPH:
1) Multi-aperture observations.
2) I don't recall the value for 4151, but for NGC 3227, the only clear-cut Seyfert in this sample, it is about 5, which is much higher than for the other galaxies shown here (except 6240).

RIEKE:
The ratio for 4151 is about unity.