

Extreme Fe II emission from an *IRAS* quasar

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Summary. During an all-sky redshift survey of *IRAS* galaxies, we have discovered a very unusual quasar (*IRAS* source 07598+6508). The optical spectrum is dominated by extremely strong Fe II emission, roughly an order of magnitude stronger than that seen in so-called strong Fe II emitters. There seems to exist a very small class of super-strong Fe II emitters. Current photo-ionization models do not readily account for the extreme properties of these objects.

1 Introduction

IRAS sources at $60\mu\text{m}$ can be used to select complete all-sky samples of galaxies, of which only a small percentage are active (Rowan-Robinson *et al.* 1986; Lawrence *et al.* 1986; Leech *et al.* 1986; Lawrence 1988, and references therein). We have selected a random sample of one-in-six *IRAS* galaxies and have been undertaking a redshift survey to study cosmological structure on a scale of ~ 200 Mpc. (Some early results are described by Efstathiou (1988)). In the course of our survey, we have found some Seyfert galaxies and a few quasars. One of the quasars is extremely unusual and is described in this paper.

Table 1 lists properties of *IRAS* 07598+6508. No identification with a catalogued object is given in the Point Source Catalog. Note that the infrared (IR) colours are typical of active galactic nuclei (e.g. Miley, Neugebauer & Soifer 1985; Ward *et al.* 1987) in showing a slope [$d\log(F_\nu)/d\log(\nu)$] of ~ 1 from 12 to $60\mu\text{m}$, followed by a flattening to $100\mu\text{m}$. Table 1 lists the positions of two stellar objects, both approximately of magnitude 15–16, found by examination of Palomar Sky Survey plates. Our optical observations of the closest object (star A) show it to be a quasar, and we therefore identify it with the *IRAS* source.

Table 1. Observations of IRAS 07598+6508.

1950.0 POSITIONS :

STAR A	RA = 07 59 53.2	DEC = 65 08 22
STAR B	RA = 07 59 50.7	DEC = 65 08 32
IRAS SOURCE	RA = 07 59 52.9	DEC = 65 08 21

IRAS ERROR ELLIPSE 32" x 6" at position angle 102.0

IRAS FLUXES, Jy $S_{12}=0.24$ $S_{25}=0.62$ $S_{60}=1.75$ $S_{100}=1.87$

WHT / FOS OBSERVATION LOG

Dec 28, UT 0104, exp = 100 sec,
 Dec 28, UT 0111, exp = 200 sec.
 Dec 29, UT 0311, exp = 200 sec.

DERIVED PROPERTIES

$z = 0.1483$
 $\text{Fe II } \lambda 4570 / \text{H}\beta \sim 4 - 8$
 $L(60\mu) = 1.1 \times 10^{46} \text{ erg s}^{-1} \quad (H_0 = 50)$

2 Optical spectrum of IRAS 07598+6508**2.1 WHT OBSERVATIONS**

Observations were made with the Durham–RGO Faint Object Spectrograph (FOS) on the new 4.2-m William Herschel Telescope (WHT), at the Observatorio del Roque de los Muchachos, La Palma, Spain. We were carrying out the northern part of our redshift survey, during the initial mixed commissioning/research phase of the WHT. The FOS is a high-efficiency low-dispersion fixed-format red-sensitive spectrograph, with CCD detector (Breare *et al.* 1987; Allington-Smith *et al.* 1988). Star A was observed several times (see Table 1). The data obtained on 1987 December 29 are shown in Fig. 1. Consistency of features between the spectra indicates that signal-to-noise is approximately 50. The observations were not of absolute photometric quality, but relative photometry should be good to about 10 per cent over 5000–8000 Å. Following our discovery, both stars A and B were observed by D. Carter on 1987 December 28, using the IPCS/IDS combination on the 2.5-m Isaac Newton Telescope. These observations indicate that star B is a normal K star.

2.2 SPECTRAL PROPERTIES; STRENGTH OF FE II EMISSION

The flux density F_ν is fairly flat as a function of wavelength, as is typical for quasars (e.g. Richstone & Schmidt 1980). A strong broad emission feature is apparent at ~ 7536 Å (peak wavelength), the red wing of which is heavily cut into by atmospheric absorption. Otherwise the spectrum is dominated by a large number of features, which give it a ‘choppy’ appearance. The position of the strong feature is uncertain to within a few Å because of atmospheric absorption, but if we identify it as H α , two of the other peaks are coincident with the expected position of H β and He I 5876. These identifications imply a redshift of 0.1483. Assuming $H_0=50 \text{ km s}^{-1}$ and $\Omega_0=1.0$, the 60- μm flux then implies a luminosity $\nu L_\nu(60\mu\text{m})=2.8 \times 10^{46} L_\odot$.

The remaining features in the spectrum are almost certainly all due to extremely strong, heavily

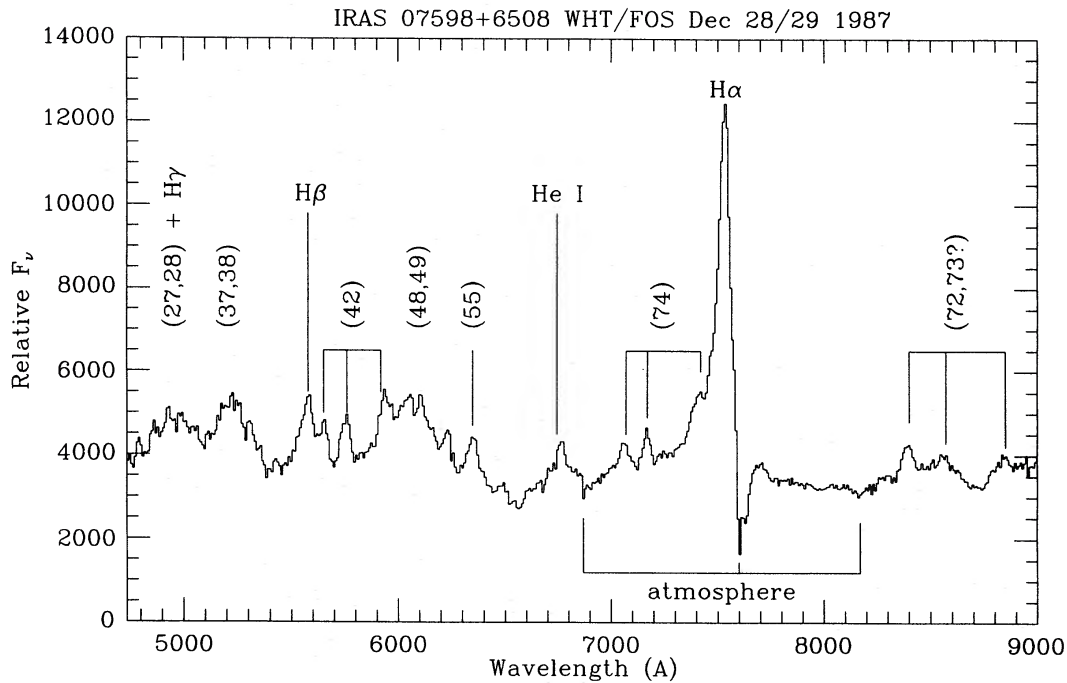


Figure 1. Optical spectrum of *IRAS* 07598+6508, taken with Durham-RGO Faint Object Spectrograph on the William Herschel Telescope, 0311 UT 1987 December 29. Pixel size is 8.7 \AA , resolution (FWHM) is $\sim 15 \text{ \AA}$. The observation was taken at 1.24 airmasses, and with slit close to the parallactic angle. A standard extinction correction has been applied. (RGO technical note 31). Line identifications are shown. Numbers in brackets are multiplet numbers for Fe II. (Note that the position of the labels mark the observed features rather than the expected positions of individual transitions within the multiplets identified with those features.)

blended emission from optical Fe II multiplets. Some of the multiplets previously observed in active galaxies (e.g. Phillips 1978; Bergeron & Kunth 1984) are labelled in Fig. 1. Other emission lines normally seen in active galaxies, such as H γ , O III 5007, are swamped by the Fe II emission. It is likely that the true continuum is not seen anywhere in our spectrum; thousands of transitions from Fe II are likely to be present at some level in active galaxies, as indeed in other astronomical objects such as symbiotic stars (Penston *et al.* 1983). By fitting a model involving over 3000 transitions, Wills, Netzer & Wills (1985) have shown that in normal quasars the Fe II emission creates a false continuum which contributes significantly to the apparent continuum over the range 2000–5000 \AA . In our case it seems likely that blueward of H α the integrated Fe II emission dominates the energy output, and that it at least contributes significantly redward of H α .

We cannot accurately quantify the Fe II emission without detailed modelling, because the lines are heavily blended, and the continuum level is uncertain. Such detailed modelling, which requires an extensive atomic database and photo-ionization code, is not attempted here. However, we have tried to estimate very roughly the strength of the Fe II 4570 blend (due to emission from multiplets 37 and 38), relative to H β emission.

We modelled H β as a scaled version of H α , and Fe II 4570 as a triangular feature in the vicinity 5000–5400 \AA . The continuum level beneath H α was taken to be that seen at 8000 \AA . The blue side of the line then is reasonably fitted by two triangles, such that full width half intensity (FWHI) $\sim 3000 \text{ km s}^{-1}$, and Full Width Zero Intensity (FWZI) $\sim 12000 \text{ km s}^{-1}$ (values typical of Type 1 AGN). By trial and error, we found that the H α profile will fit H β if we assume that H α /H β ~ 4 , thus giving us an estimate of H β strength. The major uncertainty in estimating the strength of Fe II 4570, however, is the continuum level below the feature. Taking as a maximum the observed

dip between Fe II 4570 and $H\beta$, and taking as a minimum a level such that Fe II 4570 extends as far redward as the base of the fitted $H\beta$ profile, we find values of Fe II 4570/ $H\beta$ in the range 4 to 8.

2.3 COMPARISON WITH OTHER OBJECTS

Our derived value, Fe II 4570/ $H\beta$ ~4–8, has a large uncertainty, but it is clear that the properties of IRAS 07598+6508 are very unusual. Almost 3000 Seyferts and quasars are known in total (Veron-Cetty & Veron 1984). Only a fraction have suitable spectral studies, but it is clear that super-strong Fe II emission is rare. We have found only one object in the literature with comparable Fe II emission. This is PHL 1092, which has Fe II 4570/ $H\beta$ ~6 (Bergeron & Kunth 1980). We note, however, that the Seyfert galaxy MKN 231 also appears to have extremely strong Fe II emission, despite the fact that Phillips (1978) quotes a value for Fe II 4570/ $H\beta$ of only 1.36. (We are indebted to M. Ward for pointing this out.) Visual inspection of its spectrum (Boksenberg *et al.* 1977) reveals Fe II emission from multiplets 42, 48 and 49 comparable to that seen in IRAS 07598+6508, but most of the rest of the Fe II emission is disguised by the presence of broad absorption troughs and severe reddening.

A very small class of super-strong Fe II emitters therefore seems to exist; how common is this phenomenon? Strong Fe II emission tends to occur in radio-quiet rather than radio-loud AGN (see Section 3.3). The Osterbrock (1977) study of 35 optically selected Seyfert galaxies is therefore an interesting comparison. Examination of table 1 of Osterbrock (1977) shows that Fe II 4570/ $H\beta$ has a mean value of ~0.4, that 90 per cent of objects lie in the range 0.1–1.0, and that the biggest single value is 1.34. In a study of 33 low-redshift quasars, Bergeron & Kunth (1984) found a similar range of optical Fe II emission, except that this study unearthed the extreme Fe II emitter PHL 1092. (Details were published separately in Bergeron & Kunth 1980.) It would be interesting to know if the properties of IR selected active galaxies are similar. Some tens of broad-line AGN have been found so far in published IRAS follow-up studies [see Lawrence (1988), and references therein] and larger, objective lists will result, both from our own survey and the survey of ‘warm’ sources by de Grijp, Miley & Lub (1988). No statistics on Fe II strength are available, but IRAS 07598+6508 is the only super-strong Fe II emitter seen so far.

Overall it seems that moderately strong optical Fe II (Fe II 4570/ $H\beta$ ≥1) occurs in perhaps 5 per cent of objects, but super-strong Fe II emission, such as seen in IRAS 07598+6508, PHL 1092 and MKN 231, is roughly an order of magnitude rarer. However, it is important that it occurs at all, as discussed in Section 3.

3 Discussion

Line ratios in the spectra of active galaxies may vary from object to object by factors of 2 to 10, as can be seen from the ranges quoted by Kwan & Krolik (1981). However, the further order of magnitude of variation in Fe II emission for the super-strong emitters suggests that Fe II emission may have a different origin from other lines. This wide variation in Fe II emission is particularly important (a) because it seems to be connected with the division into radio-loud and radio-quiet objects, (b) because it seems to correlate with X-ray properties, and (c) because it is not readily accounted for by standard photo-ionization models. Below, we discuss these puzzles, and how the properties of super-strong Fe II emitters affect the arguments.

First, we note that in the context of photo-ionization models, Fe II lines are expected to arise in fairly specific conditions. Fe II emission in the ultraviolet (UV) occurs by transitions from energy levels around 5 eV. The optical lines, corresponding to transitions from levels between 5 eV and the ground-state, are only expected to occur when the UV lines become optically thick, so that transitions ‘leak through’ the intermediate levels. For Fe⁺ to exist in large amounts requires a low-ionization region. For the optical lines to be strong requires large electron density, ≥10¹² cm⁻³,

and large column density, $\geq 10^{24}$ atom cm^{-2} (Wills *et al.* 1985; Collin-Souffrin *et al.* 1986; Joly 1987). Energy input to such a region then requires photo-ionization of heavy elements (and consequent heating) by hard X-rays. Such conditions could occur at the rear of thick clouds, the so-called extended ionized zone.

3.1 Fe II EMISSION AND RADIO-LOUDNESS

The UV Fe II lines are strong in all objects (Wills *et al.* 1980; Bergeron & Kunth 1984), but optical Fe II emission is typically many times stronger in optically selected active galaxies than it is in radio-selected objects (Osterbrock 1977; Grandi & Osterbrock 1978). The anti-correlation of Fe II strength with radio strength has considerable scatter, however; there exist Fe-strong radio-loud objects (for example the five such objects studied by Phillips 1978), and Fe-weak radio-quiet objects. Furthermore, a selection effect may be responsible – radio loud objects tend to have wider lines, making blending worse and leading to a misplacement of the continuum and thus to underestimation of Fe II features (Wills 1987).

The super-strong Fe II emitters provide an important test, as such a selection effect could not be responsible. We have therefore searched well-known radio catalogues (3CR, 4C, and the 2.7-GHz all sky catalogue of Wall & Peacock 1985), for a source coincident with *IRAS* 07598+6508, with no success. The strongest constraint comes from the NRAO northern sky survey at 1.4 GHz, with a limit of roughly 0.15 Jy (Condon & Broderick 1987). Comparing this to the 100- μm flux of 1.87 Jy, it is reasonable to conclude that *IRAS* 07598+6508 is radio-quiet. Both PHL 1092 and MKN 231 are also radio-quiet. The sample is still small, but this strongly suggests that super-strong Fe II emission occurs preferentially in radio quiet objects.

3.2 Fe II EMISSION AND X-RAY SPECTRAL SLOPE

Recently, Wilkes, Elvis & McHardy (1988) have claimed a correlation between soft X-ray spectral index and Fe II strength (characterized by the equivalent width of Fe II 4570), in the sense that Fe-strong objects have steep spectra. Hard X-rays heat the extended ionized zone, where Fe II emission is believed to originate. Naïvely then, one would expect flatter X-ray spectra to produce stronger Fe II emission (the reverse of what is observed), unless there is an anti-correlation between hard X-ray flux and soft X-ray spectral index.

The X-ray properties of the super-strong Fe II emitters would provide a strong test of the correlation between X-ray spectral slope and Fe II emission, which so far is based on only nine objects with a limited dynamic range in Fe II strength. No source coincident with *IRAS* 07598+6508 is in any of the 4U, 3A, or A2 hard X-ray surveys, and of course there exist no *Einstein* or *EXOSAT* pointed soft X-ray observations. The nearest coincidence is 1H 0741+651 (Wood *et al.* 1987), at a distance of 1°9, and provisionally identified with MKN 78. A soft X-ray observation of PHL 1092 exists (Zamorani *et al.* 1981) but with insufficient counts to fit a spectrum. X-ray spectra of *IRAS* 07598+6508 and PHL 1092 would be highly desirable.

3.3 ENERGY BUDGET PROBLEM

Wills, Netzer & Wills (1985) found the Fe II emission in quasars to be the major contributor to the total line emission, and noted that Fe II (total)/Ly α is typically four times larger than predicted by their improved model. Even more puzzlingly, the total energy in the UV continuum, which is inferred from the number of Ly α photons and the spectral index, seems insufficient to explain the observed lines (Netzer 1985; Collin-Souffrin 1986). This may be explained by reddening, as Ly α would be affected more than other lines (Netzer 1985), but the reddening would in turn worsen

the Fe II (opt)/H β problem (Section 3.4; Collin-Souffrin 1986). Penston (1987) has suggested that the excess UV Fe II emission may be due to transitions from high energy levels of Fe⁺, excited by fluorescence with Ly α (which would thus also remove Ly α photons). Detailed computations are however required to discover if this works in practice; furthermore the optical Fe II emission would not increase.

With an energy balance discrepancy of a factor of a few, it is easy to believe that simple model enhancements (e.g. Ly α fluorescence) should solve the problem. A further factor of 10 would, however, be very difficult to understand. At the moment, we do not know the total energy in Fe II emission from IRAS 07598+6508, as we have no ultra-violet observations. According to Netzer (1985), the total energy in Fe II emission is normally dominated by the UV multiplets. Although the observed variation from object to object in UV Fe II is smaller than that seen in the optical multiplets, the UV emission does roughly correlate with optical Fe II, as can be seen from the data of Bergeron & Kunth (1984). Ultraviolet observations of super-strong emitters are obviously critical.

3.4 PROBLEMS WITH OPTICAL Fe II EMISSION

Collin-Souffrin (1986) and Collin-Souffrin *et al.* (1986) have argued that the observed strength of the optical Fe II emission, relative to other lines produced in the extended ionized zone (e.g. H β), gives rise to another problem. In the conditions required for strong optical Fe II emission, many other line ratios predicted by the photo-ionization model would not match the observations. Collin-Souffrin *et al.* (1986) therefore explored models in which high-ionization lines are made in low-density clouds, and low-ionization lines are made in separate dense thick clouds. They purposely used Kwan & Krolik's (1981) continuum shape, which is now known to overestimate X-ray emission by a factor of 6, as this increases Fe II strength. However, they found that the Fe II strength seems to increase roughly in line with the Balmer lines; Collin-Souffrin *et al.* (1986) found that they could not get Fe II 4570/H β larger than 0.5. They argued, therefore, that Fe II requires yet another kind of region, very dense and illuminated only by X-rays, or possibly not photo-ionized at all (as suggested by Collin-Souffrin 1986; Dumont & Tully 1982). Recent work has tested both of these possibilities. Collin-Souffrin, Hameury & Joly (1988) have modelled a very thick region, Compton-heated by hard X-rays. The improvement in Fe II/H β explains 'strong' but not 'super-strong' Fe II emitters, and at the expense of predicting H α /H β ~10. Such a value is ruled out for normal AGN, but for IRAS 07598+6508 the severed modelling uncertainties mean that we cannot rule out this possibility. Joly (1987) has made purely collisional models, i.e. where the heating mechanism is unspecified but collisional equilibrium is assumed. Again, the improvement explains 'strong' but not 'super-strong' Fe II emitters.

Before rejecting the basic hypothesis that all emission lines in AGN are produced by photo-ionization, other secondary assumptions involved in the photo-ionization modelling have to be considered. A large overabundance of Fe as the source of super-strong Fe II emission is a less promising possibility than might at first be thought. Fe II is a major coolant in the extended ionized zone, so that increasing Fe abundance lowers the temperature, which in turn reduces Fe II emission (Collin-Souffrin & Lasota 1988). Several orders of magnitude overabundance would probably be required to account for the super-strong Fe II emission. A further possibility is that different clouds see a different continuum, for example because of disc inclination effects (Netzer 1987); however, this route seems unlikely to be fruitful given the new results of Collin-Souffrin *et al.* (1988) on Compton-heated media. There may be scope for substantial improvements in atomic data, for improved treatment of transfer, and so on. Finally, extremely high densities (more than 10¹²) remain to be explored, although this presents severe problems in radiative transfer modelling.

It remains to be seen whether such effects can produce the order of magnitude improvement required to explain super-strong Fe II emission. In any case, we emphasize that generic models are no longer sufficient. The extreme objects should be modelled on an individual basis, and the line spectra and continua (IR, optical, UV and X-ray) should be modelled simultaneously.

4 Conclusions

We have discovered an unusual quasar with extremely strong Fe II emission. There exists a small class of super-strong Fe II emitters. They are all radio-quiet. Current photo-ionization models, designed to explain an average set of line ratios assuming an average spectrum, fail to account for such extreme Fe II emission. This is not yet definitely a failure of the assumption of photo-ionization itself, as there remain supporting assumptions to change. To have confidence in photo-ionization, however, it is essential that the individual properties of the super-strong emitters be successfully modelled.

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