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Spectropolarimetry of Compton-thin Seyfert 2s

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ABSTRACT

We present new spectropolarimetry of a sample of nearby Compton-thin Seyfert 2 galaxies (ie those with $N_H < 10^{23}\mathrm{cm}^{-2}$). We show that the detection rate of scattered broad Hα in this sample is considerably higher than in Seyfert 2 galaxies as a whole. Our results also show that in this low obscuration set it is possible to find scattered broad Hα even when the global properties of the galaxy are largely dominated by the host galaxy and not the active galactic nucleus. These results argue against the existence of a population of 'pure' Seyfert 2 galaxies.

Key words: galaxies: Seyfert - galaxies: active - polarization - scattering - X-rays: galaxies

1 INTRODUCTION

It is now well established that many Seyfert 2 galaxies show characteristics consistent with an embedded Seyfert 1 core (ie the presence of a broad line region) that is hidden from our direct line of sight by surrounding dust. This is in good agreement with the basic unified model for Seyfert galaxies (Antonucci 1993) which suggests that an optically thick circumnuclear torus, with a scale height at least as large as the broad line region itself, surrounds the active nucleus. The orientation of this torus relative to our line of sight then determines whether the galaxy is classified as a Seyfert 1 or 2 galaxy.

The detection of scattered broad Hα lines provides the firmest evidence for a hidden broad line region (HBLR) in Seyfert 2 galaxies, as has been demonstrated by, for example, Antonucci and Miller (1985), Miller and Goodrich (1990), Young et al. (1996a), Heisler, Lumsden & Bailey (1997), Moran et al. (2000), Lumsden et al. (2001) and Tran (2001, 2003). A significant fraction of all Seyfert 2 galaxies show evidence for an HBLR (eg. Tran 2001, Moran et al. 2000, Lumsden et al. 2001). This fraction increases as the luminosity of the active galactic nucleus (AGN) increases (Lumsden & Alexander 2001, Gu & Huang 2002, Martocchia & Matt 2002, Tran 2003). It is also clear that the galaxies known to have HBLRs tend to have warmer mid-far infrared colours than those galaxies without (Heisler et al. 1997, Lumsden et al. 2001 and Tran 2001, 2003).

Hard x-ray spectroscopy also allows us to investigate the cores of these galaxies even at levels of obscuration that would completely hide the broad line region in the optical (eg Maiolino et al. 1998, Risaliti, Maiolino & Salvati 1999). Alexander (2001) pointed out that the combination of the x-ray data and the spectropolarimetry ruled out the model proposed in Heisler et al. (1997) in order to explain the warmth of the infrared colours in the HBLRs. Heisler et al. suggested that the colour was simply due to the orientation of the torus and hence the obscuration to the infrared emitting zone, so that more obscured systems appeared colder. By contrast, Alexander showed that the level of x-ray obscuration did not vary on average between galaxies both with and without HBLRs. It has also been shown that the Seyfert 2s which do not show HBLRs tend to have global properties that are more in keeping with those of their host galaxies (eg. Alexander 2001, Lumsden et al. 2001, Tran 2001, 2003).

However, radically different interpretations have been reached from these data. Tran (2001, 2003) suggests that at least some of the non-HBLRs genuinely lack a Seyfert 1 core. Nicastro, Martocchia & Matt (2003) have suggested that the main difference between those Seyfert 2s showing scattered broad Hα and those without is the accretion rate of the central AGN. They suggest that the rate is simply too low in the Seyfert 2s without scattered broad Hα to support an extensive broad line region. They note that at least some of these galaxies have low inferred hard x-ray absorption, suggesting that we should be able to see the broad line region if it exists. The Nicastro et al. model is clearly compatible with Tran's observations, though the fraction of galaxies without an intrinsic broad line region should be less for suitable luminosity selected samples in the Nicastro et al. model than Tran claims to find. By contrast, Lumsden & Alexander (2001) showed that the luminosity dependence of HBLR detectability was dominant (ie suggesting more luminous active galaxies supported a larger scattering volume). Lumsden et al. (2001) further suggested that the level of obscuration was still a weak contribution to the appearance of AGN once the effects of the intrinsic AGN luminosity were allowed for, although other studies have not confirmed this result (Alexander 2001, Tran 2001, Gu et al. 2001, Gu & Huang 2002). These observations are compatible with the alternative version of the unified model given by Lawrence (1991). He suggested that the inner surface of the torus would be pushed outwards from the AGN as the luminosity increased purely because the dust sublimation radius would increase. In practice an accretion disk has a self shielding effect so the result may not be as dramtic as Lawrence suggested, but it is still a potential factor. It should also be noted that the findings of Lumsden & Alexander are not inconsistent with the Nicastro et al. result, since the accretion rate may be the fundamental parameter determining the AGN luminosity, and the presence of suitable scatterers must scale with the luminosity of the source.

The aim of this paper is to test which of these possibilities is a better match to the actual results for Seyfert 2s with known low obscuration from hard x-ray data. In these sources obscuration to the scattering sites should be effectively irrelevant if the extinction is reasonably compact. This should allow us to test the other models outlined above more easily than in previous samples which span the full range of obscuration. In order to test these ideas we have acquired spectropolarimetry at both high signal-to-noise and higher spectral resolution than in our previous observations. The latter allows a better separation of possible multiple polarising components.

2 OBSERVATIONS AND DATA REDUCTION

Our observations were acquired on the nights of 1–4 June 2002 at the Anglo-Australian Telescope. We used the RGO Spectrograph with an EEV 4096×2048 pixel CCD. Vignetting within the instrument limits the actual spectral coverage to 3296 pixels. The slit width was typically 1.5 arcseconds, matched to the approximate seeing. The effective spectral resolution of our data is ~ 3Å. Conditions were photometric on 3 and 4 June, and partly photometric on 2 June. Where fluxes are reported they are taken from the photometric data sets alone. Most sources were observed on more than one night because of the requirement for high signal-to-noise data. All were observed on at least one of the photometric nights.

A calcite prism was used to split the incoming beam into e and o-rays together with an aperture mask made up of discrete slit-lets. A half-waveplate modulated the incoming phase. Four steps of the waveplate at 0°, 45°, 22.5° and 67.5° were required to derive the full set of Stokes parameters for linearly polarized light. Sky subtraction was achieved by nodding the object into an adjacent slit-let. The sky and object spectra for the four separate waveplate positions were extracted then combined to give the final Q, U and I Stokes parameters. We extracted data from a region of between 3 and 4 arcseconds along the slit in most cases.

We also obtained observations of polarised and unpolarised standard stars in order to check the system efficiency and calibrate the position angle data. The results showed good agreement with published values for the polarised standards, and confirmed that the system polarisation was less than 0.1% from the unpolarised standards.

We selected our targets from the catalogue of Seyfert 2s with previously available x-ray spectroscopy given in Bassani et al. (1999). We imposed only two criteria: that the object was sufficiently southern to be observable from the AAT, and that it had an inferred neutral hydrogen column density $< 10^{23}$cm^{-2}. We did include two other targets in the sample as well to fill gaps in the RA distribution. These were IC5063, previously known to show broad scattered Hα but for which spectropolarimetry of the Hβ region does not exist, and NGC6300, which is not listed in Bassani et al. (see Risaliti 2002 for x-ray data). Both of these have $N_H \sim 2 \times 10^{23}$cm^{-2}. We integrated on source until we had a clear detection of an HBLR or for approximately 8 hours. The final signal-to-noise is similar to the data presented in Lumsden et al. (2001), though at an effective spectral resolution that is 2.5 times higher. The full list of all seven sources, including the individual integration times, is given in Table 1.

All of our targets are relatively bright x-ray sources, and most of the low column density targets fall within the sample of narrow line x-ray galaxies identified in the sample of Ulvestad & Wilson (1989). These observations therefore provide a useful comparison sample to that of Moran et al. (2000), since they obtained spectropolarimetry of the classical Seyfert 2s in the Ulvestad & Wilson sample, but not the narrow line x-ray galaxies. In practice some of our targets have previously been classified as Seyfert 1.8 or 1.9. We opted to observe these sources as it is not clear whether the weak broad component seen in direct light is scattered in any event. We therefore count all such classification as Seyfert 2s.

The data were reduced in a standard fashion to give Q, U and I Stokes parameters. Since the normal definition of polarisation is a positive definite quantity, we prefer to work with the rotated Stokes parameter Q'. This is the result of rotating the Stokes parameters through an angle consistent with the measured position angle. The net result is that virtually all of the significant polarisation information is rotated into the new Q' parameter. Of course this is only strictly valid when the position angle is approximately constant with wavelength. This is largely true for our data, since the observed variation with wavelength is always small. The actual observed mean position angle is given in Table 1.

Line fluxes were measured from both the total intensity and polarised flux data. The fluxes are taken from Gaussian line fits. All narrow lines required at least two component fits to match the resolved line structure. Where necessary we also fitted a component to broad Hα in the direct light spectrum. There was no need to fit a component to broad Hβ for any object in the direct light spectrum. The fitted components were constrained so that, for example, the wavelengths of the line centres of the two [NII] lines around Hα, and their relative intensities, matched theoretical expectation. We only fitted a single Gaussian where a broad component to Hα is clearly present in the polarised light spectra, since this adequately accounts for all of the flux and there is no evidence for a strong polarised narrow line component (as evidenced in Figure 1 by the generally weak or absent

[OIII] 5007Å line in polarised light). The exceptions to this are NGC 2992 and F18325–5926 which are discussed further in Section 3. In these cases we allowed for the narrow line contributions as well. Where broad Hα was not present in the polarised flux, we estimated limits to the broad Hα line assuming a line width of 3500kms^{-1} (the mean from the sample of Seyfert 1s in Stirpe 1990). The resultant observed scattered broad Hα fluxes are given in Table 1. Our deepest limit, for NGC 5506, is approximately a factor of two lower than for any of the non-detections reported in Lumsden et al. (2001). It is worth noting however that all of the detections we report here have broad Hα fluxes that lie above the limits we found for the non-detections in Lumsden et al. (2001), so it is fair to compare the results of this survey with the earlier work. The key results are given in Table 1 with the observed (not extinction corrected) fluxes for [OIII] 5007Å and the broad Hα component seen in scattered light.

3 RESULTS

The basic results of our observations are shown in Figure 1. This Figure shows the direct light spectrum, I, the rotated Stokes parameter, Q$'$ and the percentage polarisation. Three of our seven sources (NGC 7314, MCG-5-23-16 and IC 5063) show clear evidence for broad Hα in the polarised flux. Of these, NGC 7314 and MCG-5-23-16 were not previously known to contain HBLRs. IC 5063 was previously found to contain a HBLR by Inglis et al. (1995), and that result is confirmed here. None show any evidence for scattered Hβ however.

The nature of the other four sources we observed required further analysis. There are clear features present in the polarisation for NGC 2992 and F18325–5926, though the polarised flux is dominated by emission from the narrow line region. It is possible to decouple different polarisation mechanisms where there is evidence for a change in polarisation with wavelength. For example, if the bulk of the polarisation observed is due to dichroic absorption in the host galaxy, but any broad lines present are scattered, there is no *a priori* reason for the position angle, or the degree of polarisation, of the two mechanisms to be the same. We can subtract off the smooth component (whether due to dichroic absorption or large scale scattering is irrelevant) to leave only the polarisation due to the scattering from the broad line region. In practice, we fit a low-order polynomial to the Q'/I data to derive the smooth component. The residual is then rescaled by the total intensity to give a polarised flux spectrum as shown in Figure 2.

We applied this procedure to the four sources that did not show immediate evidence for broad Hα to determine if there was evidence for a masked scattered component. Both NGC 2992 and F18325–5926 exhibit behaviour of this kind, as indicated by their polarisation spectra. The resultant polarised flux for these objects after removal of the smooth component is shown in Figure 2, revealing clear broad Hα. Again this is the first detection of scattered broad Hα in these galaxies. Both also show some evidence for broad Hβ as well. The remaining two sources, NGC 5506 and NGC 6300, do not show any evidence for broad Hα however. We have given limits to the broad Hα line as noted in Section 2. Overall we detect a clear signature of scattered broad Hα in 5 out of 7 sources.

It is worth briefly considering the non-detections, NGC 5506 and NGC 6300. NGC 5506 is the more interesting case. Nagar et al. (2002) present compelling evidence that NGC 5506 is an obscured narrow line Seyfert 1 based on near infrared spectroscopy. In keeping with previous papers by us however we do not class this object as an HBLR, which we define strictly as those galaxies showing polarised broad Hα. It clearly has a very low column density to the x-ray source (Risaliti 2002). However, NGC 5506 is almost edge-on, and has a conspicuous dust lane, so the obscuration is on considerably larger scales than in the other galaxies we have studied. The polarised flux is consistent with a dichroic origin, from dust in front of the narrow line region. There is certainly no evidence that we can see the narrow line Seyfert core, since the intrinsic line width found by Nagar et al. (and Veilleux, Goodrich & Hill 1997) in the near infrared is considerably broader than the optical lines. Equally, there is no reason to suspect that a narrow line Seyfert 1 should not support an extensive scattering region if it is luminous enough. Therefore the most likely cause of the non-detection is the extent of the obscuration rather than the actual amount. We can say less about NGC 6300, since it is the least luminous galaxy and although the limits we can place on broad Hα are strict, they are not inconsistent with previous limits for galaxies of this luminosity. Therefore we cannot say whether the source has an HBLR that is too faint to detect with the current instrumentation or lacks an HBLR completely.

4 COMPARISON WITH PREVIOUS SURVEYS

4.1 Overall detection rates

Our new data clearly indicate that it is possible to detect HBLRs in most low obscuration Seyfert 2s. We can extend this result slightly by considering all of the low obscuration Seyfert 2s in the Bassani et al. (1999) sample. There are another six galaxies with $N_H < 10^{23}$cm^{-2} for which spectropolarimetric data exists. Four show HBLRs (05189–2524, NGC 5252, 20460+1925, 23060+0505: Young et al. 1996a,b), the other two do not (NGC 7172, NGC 7590: Lumsden et al. 2001, Alexander et al. in preparation). It should be stressed however that the signal-to-noise of the polarimetry for the latter two objects is not as good as for NGC 5506 for example. Despite this, and although these samples are not complete, the indication is that the detection rate of HBLRs in low obscuration Seyfert 2s is higher than in the population as a whole (eg. see the overall detection rate as given in Lumsden et al. 2001, Tran 2001 or Moran et al. 2000). This ties in with the previously more tentative suggestion in Lumsden et al. (2001) that it is easier to find HBLRs at low column density. However, similar high spectral resolution observations of a suitable sample of Compton-thick Seyfert 2s is required to test this directly.

We can also compare our results on the Seyfert 1.8/1.9 galaxies in our sample with those of Goodrich (1989). Noteably, all of the galaxies that would be classified as a Seyfert 1.9 by us also show an HBLR. Goodrich (1989) by comparison found that only a small fraction of his targets showed evidence of an HBLR. It is not clear if this difference is due to our selection being amongst the brighter members of this class (which maybe why they fall into the narrow line x-ray galaxy class of Ulvestad & Wilson), or to poorer signal-to-noise in Goodrich's data. Extra studies would certainly be worthwhile to determine if HBLRs are common characteristics of other members of this class.

4.2 Infrared, radio and x-ray diagnostics

We have not yet considered the other properties of these galaxies, and how they fit into any overall picture. In previous papers we showed that the other key factors in determining HBLR visibility were the core luminosity of the AGN and the contrast of the AGN and host galaxy luminosities (and, perhaps, obscuration). In order to avoid problems with varying signal-to-noise data we only consider the galaxies with spectropolarimetry presented in this paper. Unfortunately, MCG-5-23-16 lies in the IRAS gap region, and therefore has no far infrared data available, so it is not included.

The mid-to-far infrared colours were shown in both Heisler et al. (1997) and Lumsden et al. (2001) to be a good discriminator between galaxies with HBLRs and those without, and also a good indicator of the ratio of host galaxy and nuclear luminosities (Alexander 2001). In particular, previously known HBLRs have IRAS colours similar to those of a reddened Seyfert 1, whereas most non-HBLRs have colours that are very similar to a star forming galaxy. Another good discriminator as to the activity present is the ratio of low frequency radio data with the far-infrared flux (Lumsden et al. 2001 and Tran 2001, 2003). We used 20cm NVSS data (Condon et al. 1998), which has the drawback of sampling much of the emission from the host galaxy as well as the AGN. However, the radio data should be dominated by the AGN except at the lowest luminosities. This is clearly true for the sample considered here since the comparison of radio and absorption corrected hard x-ray luminosities shows a scatter of less than 30%.

The data for the galaxies presented here gives a somewhat different picture to that presented by Tran (2001, 2003: Figure 3, and compare with similar figures in Lumsden et al. 2001). Two of the HBLRs have infrared colours consistent with star forming galaxies (NGC 2992 and NGC 7314), and one of the non-HBLRs has the colour of a reddened Seyfert 1 (NGC 5506). This result indicates that it is possible to find relatively low luminosity Seyfert 1 cores in galaxies whose global properties are dominated by their host galaxies rather than the nucleus. In particular, we stress that some of the HBLRs in this sample have flux ratios $F_{60}/F_{25} > 4$, cooler than any found previously. The same is true for the far-infrared/radio comparison. Again, the HBLRs are not confined to the AGN dominated region. Tran (2001, 2003) made much of the absence of HBLRs from the lower left of his equivalent of Figure 3(b) (which in our plot is actually the lower right). This argues strongly against the simple split between a group of Seyfert 2s without an HBLR and those with as Tran proposes.

Nicastro et al. (2003) have recently suggested that the difference between a detection and a non-detection may actually lie in the accretion rate onto the central black hole. The accretion rate can be constrained by the hard x-ray flux, and the mass of the central black hole by the extinction corrected bulge luminosity (though with larger scatter). We have applied their technique for estimating the accretion rate to our sample where suitable data exists. The results are shown in Table 1. Our results indicate that all of our sources, HBLRs and non-HBLRs alike, lie above the minimum accretion rate of 10^{-3} of the Eddington rate suggested by Nicastro et al. This sample may not be the best to test the Nicastro et al. suggestion however, since all of the Seyfert 2s considered here, apart from NGC 6300, are relatively luminous compared to the whole local AGN population, and X-ray selected AGN as a class are also unlikely to have a low accretion rate. We discuss a better test of the Nicastro et al. results in Lumsden & Alexander (2003, in preparation).

5 DISCUSSION

Our new results on Compton thin Seyfert 2 galaxies indicate that most show evidence for an HBLR. The exceptions are NGC 5506, which has very extended obscuration but is known from infrared spectroscopy to have a narrow line Seyfert 1 core, and NGC 6300 for which we do not have sufficient signal-to-noise to definitely state whether an HBLR is present or not. At least one factor in our success rate in detecting HBLRs is the higher spectral resolution data we have acquired. This makes it much simpler to detect weak broad scattered lines masked by polarised narrow lines as shown in Section 3. Our results also show counter examples of HBLRs in the 'pure' Seyfert 2 region of radio/infrared colour space proposed by Tran (2001, 2003), and for the first time we find HBLRs in galaxies with cool far-infrared colours ($F_{60}/F_{25} > 4$). This strongly suggests that the split proposed by Tran is not as simple as appears from his data.

It is still worth considering briefly the evidence for a class of Seyfert 2s lacking a broad line region. Nicastro et al. (2003) have shown that at least some of the 'pure' Seyfert 2s identified by Tran must have very low accretion rates. However, some caution must be applied. X-ray and spectropolarimetric data are rarely contemporaneous, and it is known that there can be wide variations in the observed level of x-ray flux with time (eg Turner et al. 1997). A good example to consider here is the case of NGC 2992, which has varied in x-ray luminosity by over an order of magnitude in the last twenty years (Gilli et al. 2000), reaching a maximum again recently. Our spectropolarimetry coincides with this rise to maximum. At minimum, NGC 2992 would have fallen well below the minimum accretion cut-off suggested by Nicastro et al. The narrow line region responds much less to such variability in the central engine since it is spatially much larger, and hence the lag between the inner and outer edge tends to smooth out variations. Longer timescale monitoring of the x-ray properties of the low accretion rate Seyfert 2s would be useful in determining if their lack of an HBLR is due to some intrinsic difference in the Seyfert 2 population as a whole (which we would argue against) or simply that they are in a low state. Once accretion stops completely such objects would rapidly lose their narrow line regions as well, and cease to classed as Seyfert 2s.

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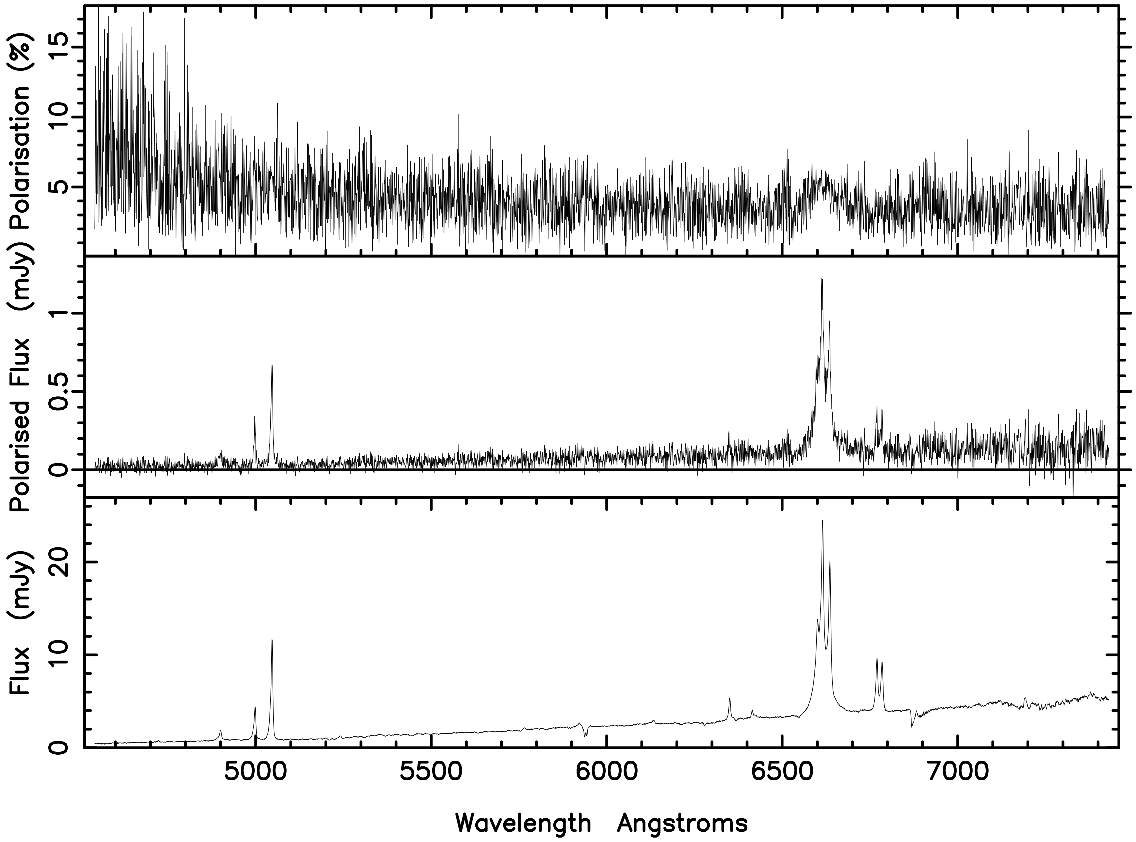
Name	cz	Exp. Time	$F_{\lambda 5007}$	$F_{\lambda 6563b}$	$H\alpha/H\beta$	$W_{\lambda 5007}$	L/L_E	θ
	(kms^{-1})	(s)	(10^{-13}ergs/s/cm^2)	(10^{-15}ergs/s/cm^2)		(Å)	10^{-3}	$^\circ$
NGC 2992	2310	9600	2.8	19.6	5.3	85	5.1	35
MCG-5-23-16	2480	9600	5.6	42.6	2.0	51	19	
NGC 5506	1850	33600	12.5	<1.0	4.9	595	7.3	80
F18325–5926	6060	28800	10.7	22.4	3.5	15		
NGC 7314	1420	14400	2.0	5.6	4.8	164	2.3	5
NGC 6300	1110	28800	1.4	<1.3	8.7	36	1.3	35
IC 5063	3400	3360	9.5	29.6	4.3	160	2.4	8

Table 1. Observed properties of our sample. The exposure time in seconds refers to the total on source time. $F_{\lambda 5007}$ is the observed [OIII] 5007Å line flux, $F_{\lambda 6563b}$ is the observed broad component to the scattered Hα flux (or the limit that can be placed on it) as discussed in Section 2, Hα/Hβ is the observed Balmer decrement from the narrow line component fits. $W_{\lambda 5007}$ is the observed [OIII] 5007Å equivalent width and is partly a measure of the intrinsic ratio of AGN and host galaxy. L/L_E is the predicted ratio of the nuclear luminosity to the Eddington luminosity derived in the same fashion as Nicastro et al. (2003), and is a measure of the accretion rate. This column is left blank if the appropriate data to calculate this quantity do not exist.

(a)



(b)

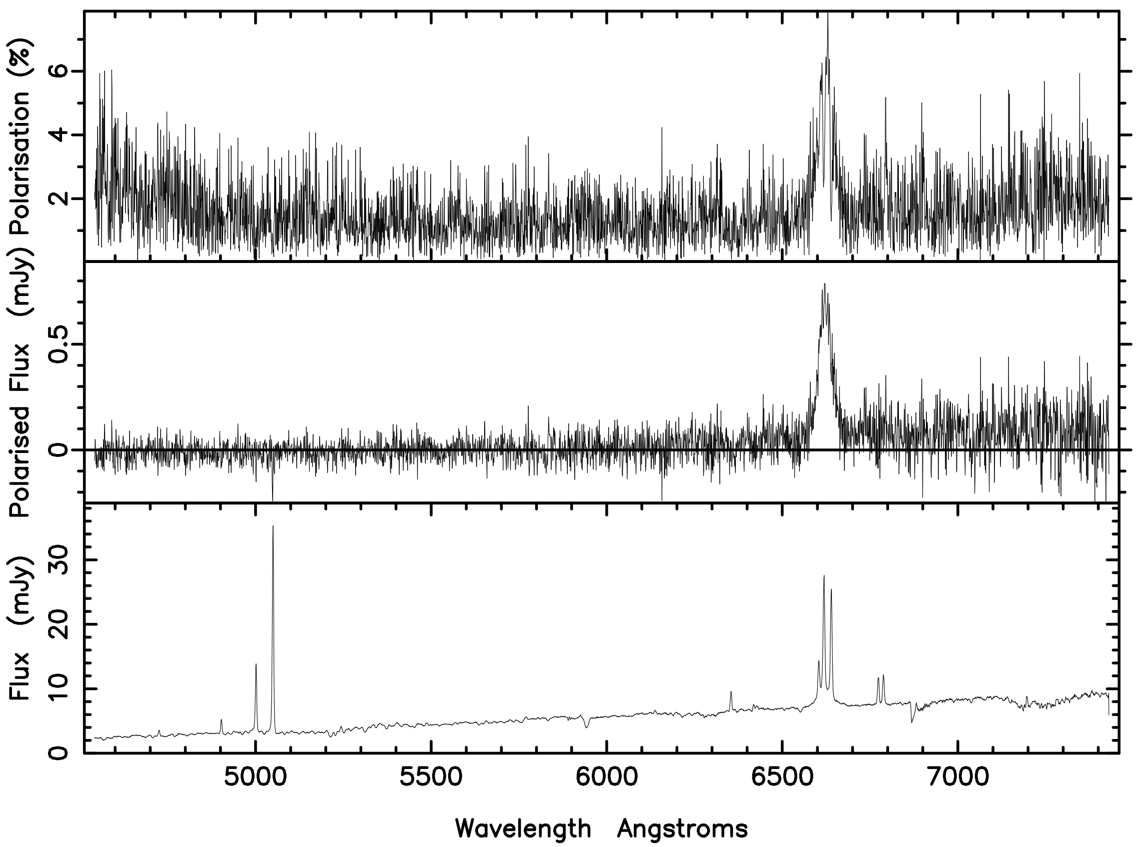
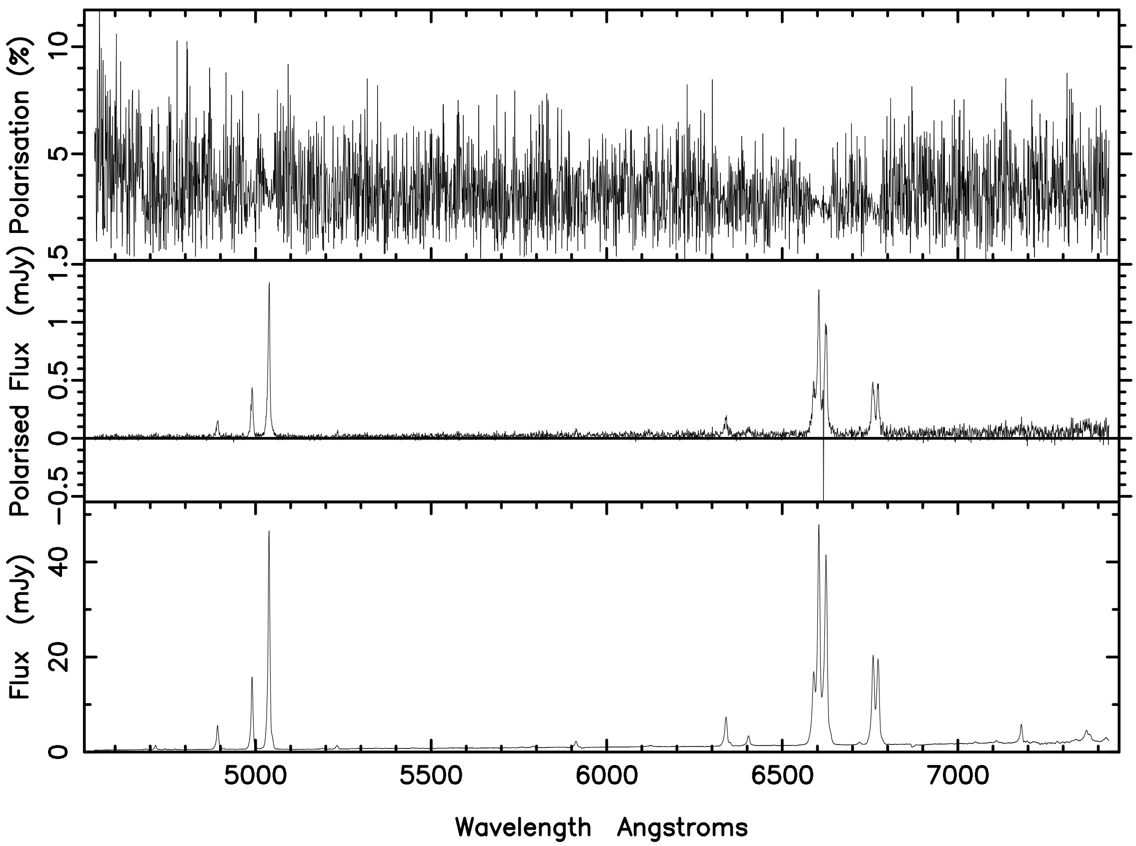


Figure 1: Spectropolarimetric data for our sample, showing in each case, from top to bottom, the observed position angle, the rotated Stokes parameter Q' and the total intensity. The data are unbinned. The plots are for (a) NGC 2992 and (b) MCG-5-23-16.

(c)



(d)

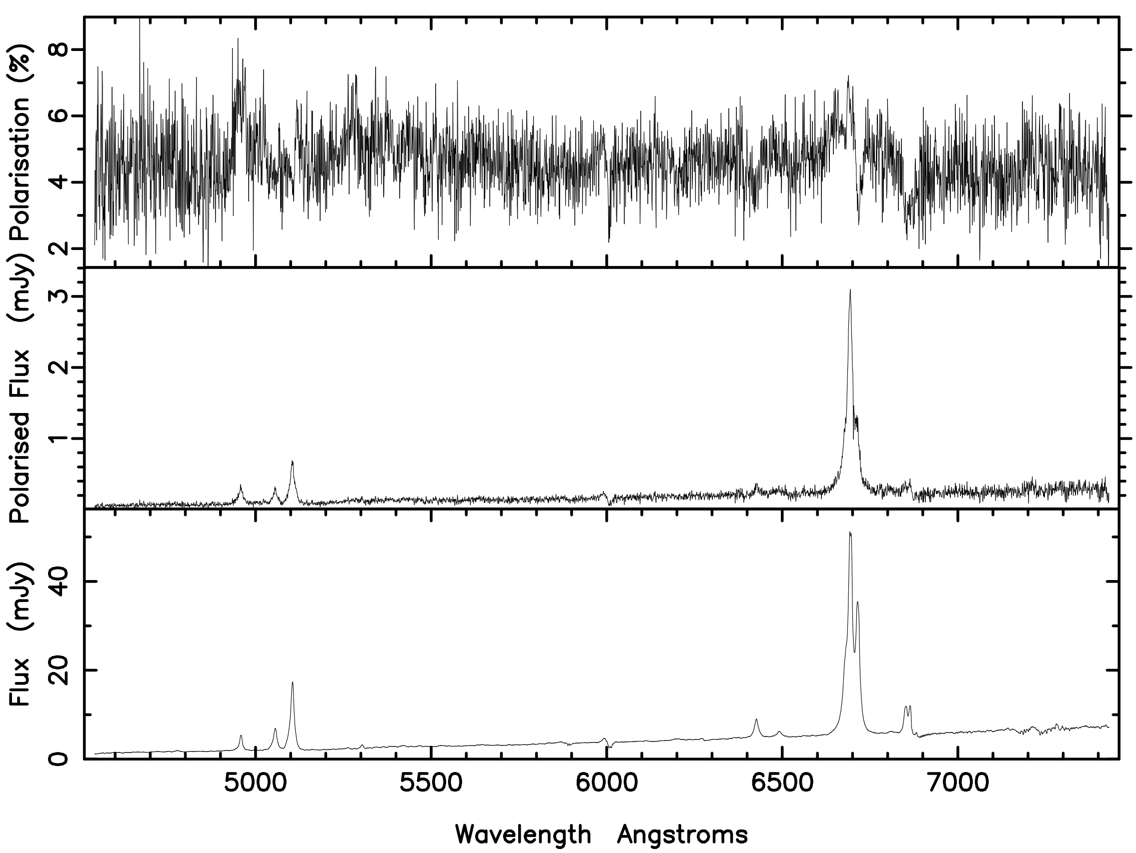
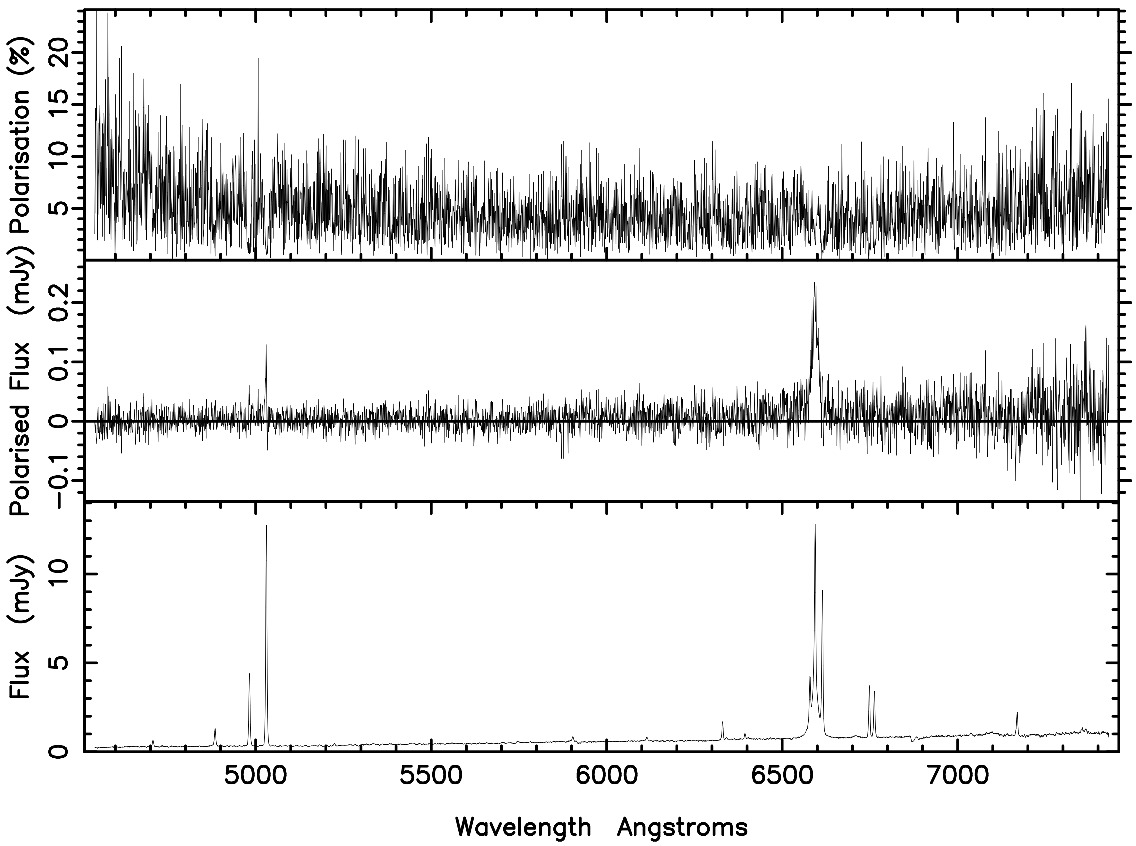


Figure 1 continued: (c) NGC 5506 and (d) 18325–5926.

(e)



(f)

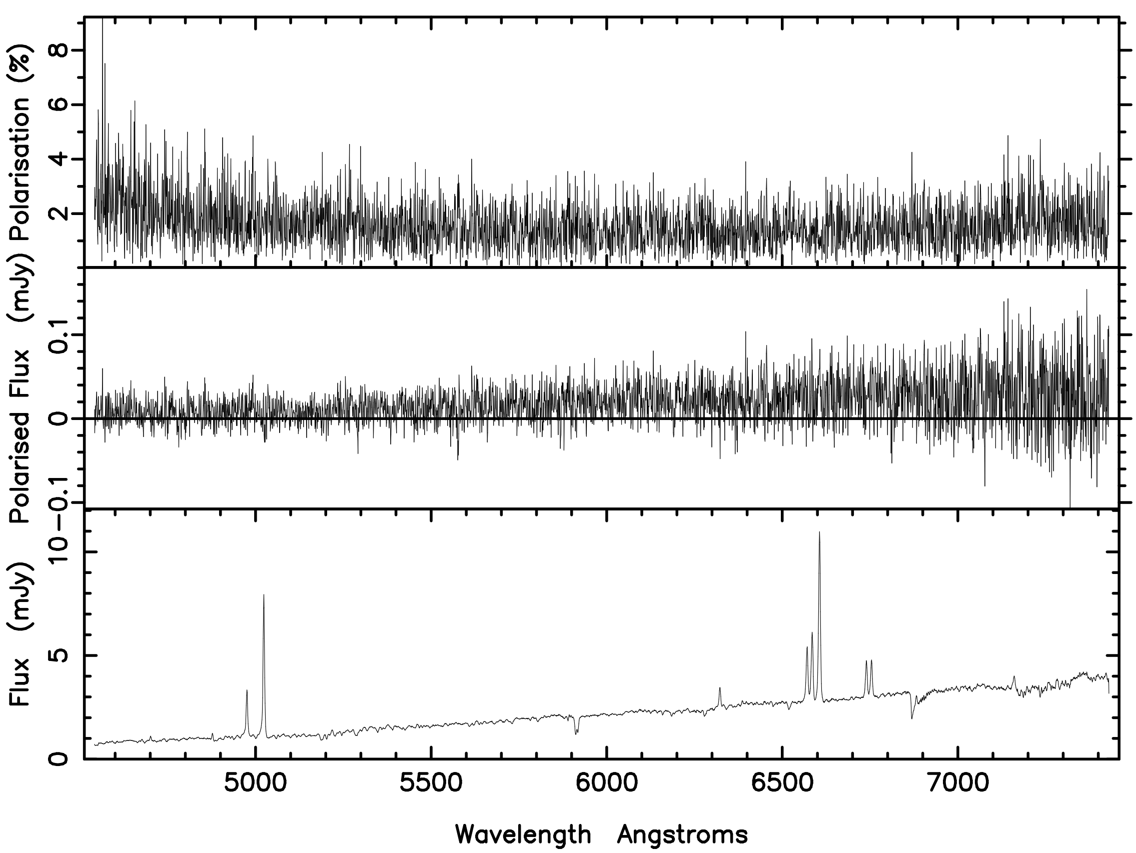


Figure 1 continued: (e) NGC 7314 and (f) NGC 6300.

(g)

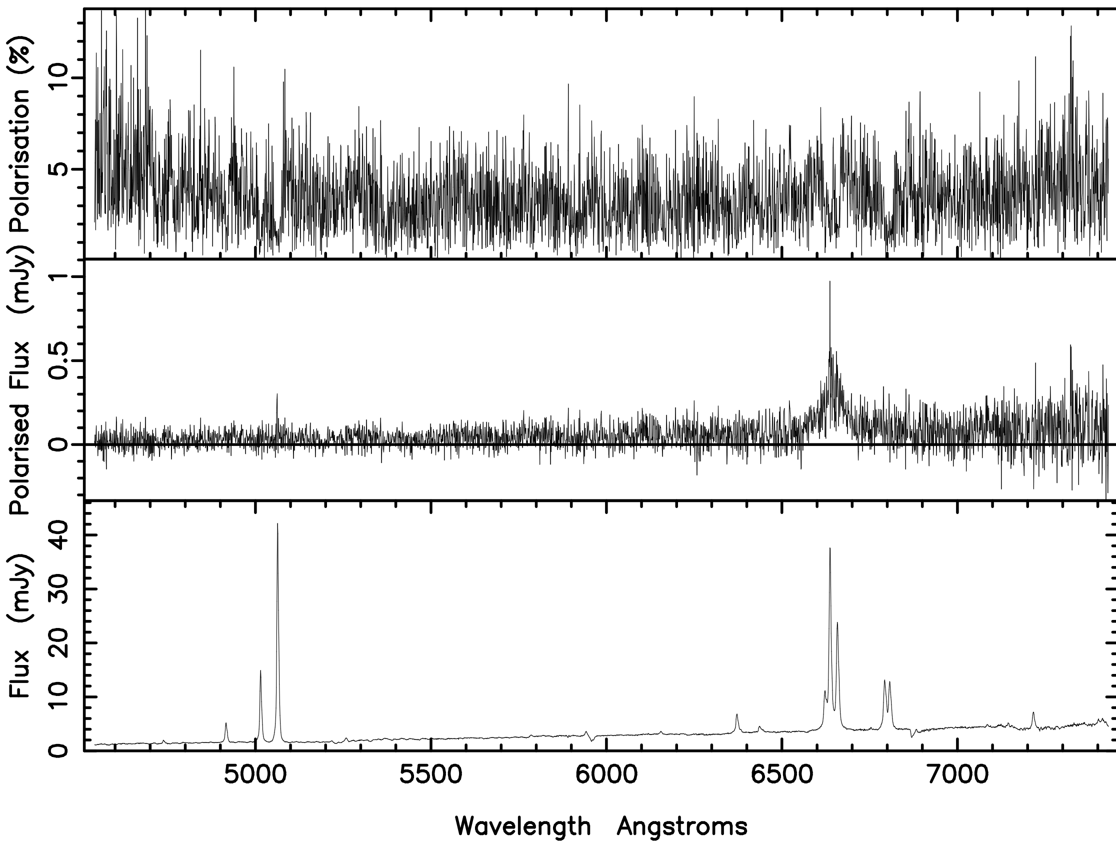


Figure 1 continued: (g) IC 5063

(a)

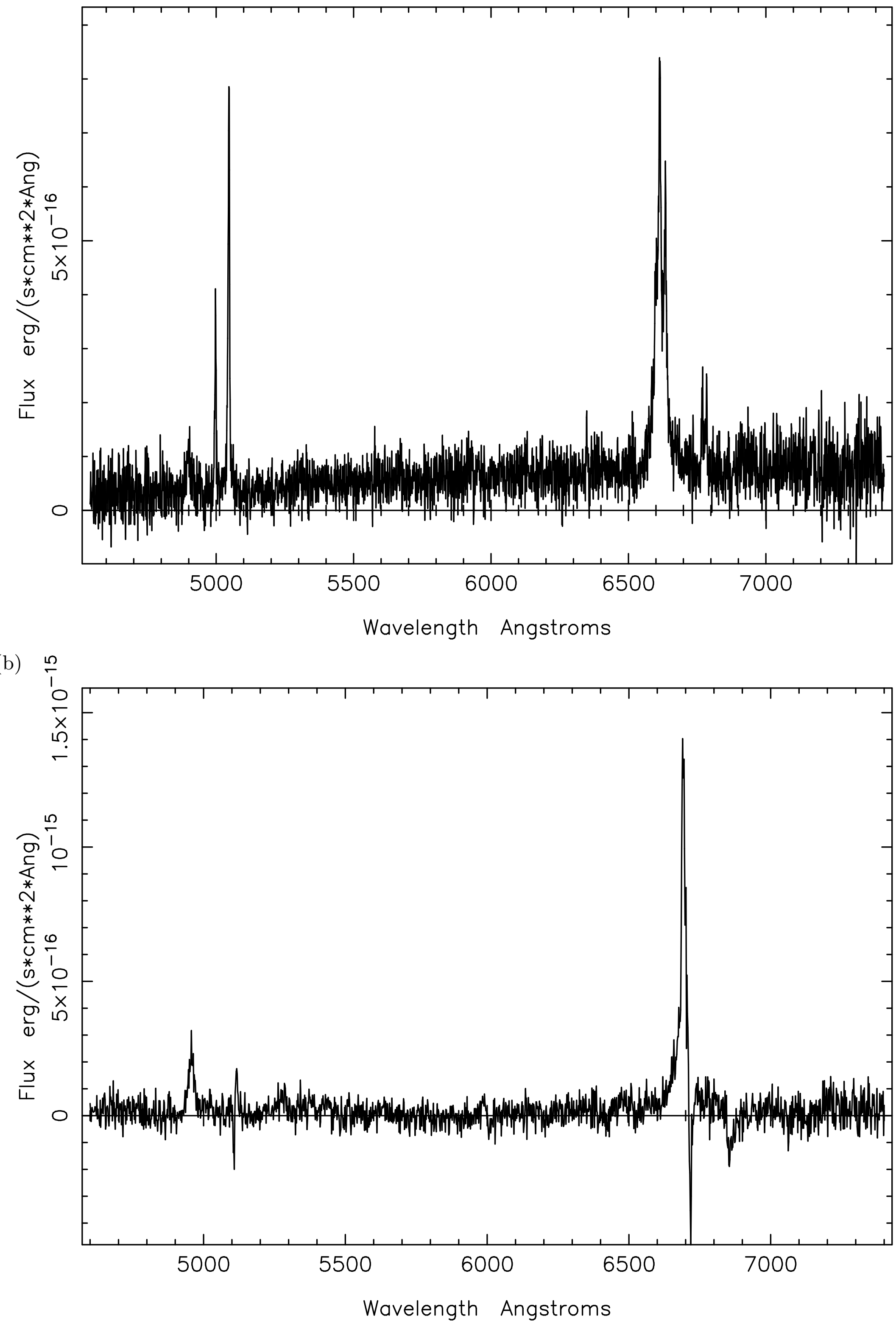


Figure 2: Residual polarised flux after removal of the 'smooth' component in the polarisation. Data are shown for (a) NGC 2992 and (b) 18325–5926. The negative feature near Hα in (b) is due to the overcorrection of narrow [NII]. Broad Hβ is evident in addition to a broad Hα component in both sources.

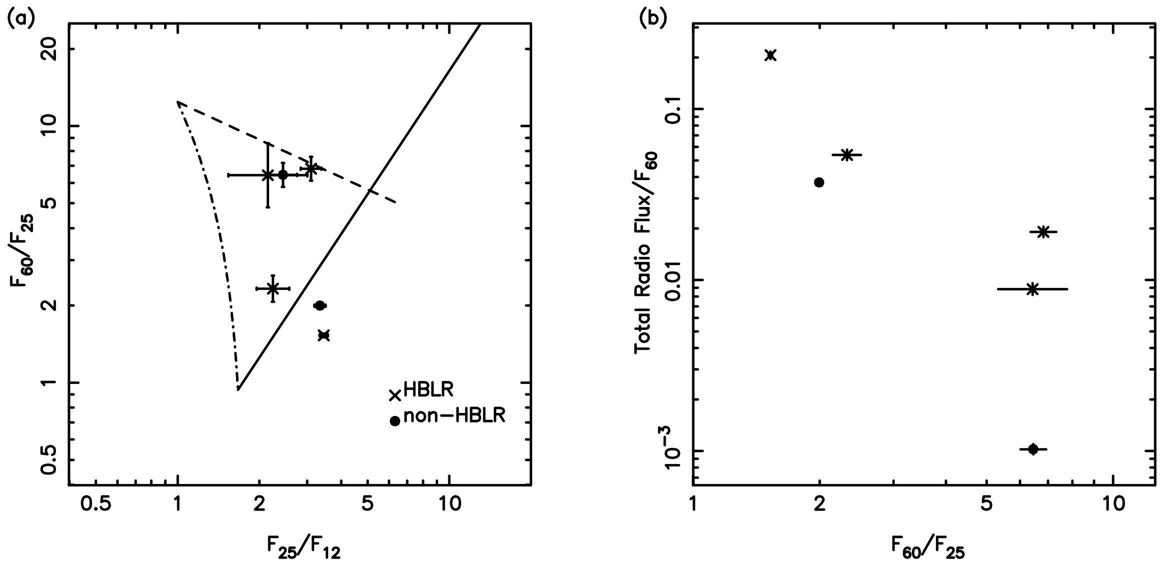


Figure 3 (a) Infrared colour-colour plot similar to that presented in Lumsden et al. (2001). The solid line represents the track of a suitably reddened Seyfert 1, the dashed line represents the mean for the local starburst population and the dot-dash line is the limit for mixing between the two types. We clearly find HBLRs in galaxies with cool colours consistent with a starburst origin for the infrared emission. (b) Infrared-radio colour-colour diagram, similar to that presented in Lumsden et al. (2001) and Tran (2001, 2003). Powerful AGN cluster in the top left of this diagram. However, we also find HBLRs in galaxies in the lower right region that Tran describes as being populated by 'pure' Seyfert 2 galaxies.