Galaxy studies

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Active Galaxies in Radio and IR

The 1960s decade was a time when many new phenomena were discovered thanks to observations becoming possible beyond the visible and radio bands. Active Galactic Nuclei were among the most exciting of these discoveries. They soon began to be investigated at as many wavelengths as possible.

In particular, the few Seyfert galaxies known in the early 1970s, of course nearly all northern objects, were found to emit strongly in the infrared. For example, Penston et al (*MNRAS* **169**, 357, 1974) had interpreted their optical-to-infrared colours as mixtures of ordinary galaxies with nuclear sources having strong UV and IR emission. In addition, they found some evidence for variability in a few cases.

Having a generous allocation of time on the 74-inch telescope in Pretoria and later Sutherland, I felt that this was an area to which I could make useful contributions. What follows is about my work only, though often with collaborators, and is not a general review. Around June 1972, as soon as I could, during the three years when I was visiting SAAO from the RGO, I started to observe "active" galaxies. It should be remembered that, at that time, the Southern Schmidt sky surveys had not yet been published and only very few galactic nuclei had been photographed with high resolution, with the result that, especially in the south, very few active nuclei had so far been discovered. The 74-inch was then, with its cousin at Mount Stromlo in Australia, the largest telescope in the Southern hemisphere and therefore potentially the most sensitive in the infrared. In some ways, interesting and rather fundamental results were there for the plucking.

Some points concerning the observation of active galaxies

Active galactic nuclei are relatively easy to set on because they are generally star-like and conspicuous relative to their host galaxies. Occasionally, when I worked with small apertures, I used a guide star and chart recorder to "peak up" to make sure the nuclei were correctly centred. Usually I worked at a fixed aperture of 12 arcsec diameter with the 1.9m telescope. This diameter represented a compromise that was realistic under most seeing conditions and allowed photometry with a precision of around 3% or better. On some occasions, multi-aperture observations were made so that the contribution of the underlying galaxies could be estimated (Occasionally, of course, the seeing was too poor to make observations). The star-sky chopping distance was about one arcmin N-S in the earlier observations and about 30 arcsec later on, with a few at 12 arcsec in the earlier days. As usual with my infrared photometry, the star and sky positions were interchanged every 20 seconds. For many bright nuclei the contribution of background galaxy to the reference beam was negligible.

Today, array detectors would be used for this type of work but these did not become available with the necessary precision until after the end of the programme.

Early programmes

Since there were then no lists of southern Seyferts, I selected at first galaxies with bright nuclei such as the objects in the paper "Peculiar Nuclei of Galaxies" by Sersic and Pastoriza (*PASP* **72**, 287, 1965). These were described as having "hot spots" or "amorphous nuclei". My first paper in this field was about the members of the well-known quartet consisting of NGC 7552, 7582, 7590, and 7599 (*MNRAS* **162**, 35p, 1973). I found that their NGC positions were for some reason not accurate and I got some measurements done by TW Russo from a CAZ plate taken at the Observatory in Cape Town. Their star-like nuclei were bright enough to show up on Astrographic plates!

The early results on the Sersic and Pastoriza objects were most interesting as their JHKL (1.25, 1.65, 2.2 and 3.4μm) colours were unlike those of ordinary galaxies but showed infrared excesses particularly at L or longer wavelengths, typical of Seyferts. Peter Andrews of the Radcliffe Observatory helped me by getting visible-region colours (Glass, *MNRAS* **164**, 162, 35p).

My first major paper was *The JHKL Colours of Galaxies* (Glass, *MNRAS* **164**, 155, 1973) containing results for the nuclei of 27 southern galaxies. It created quite a lot of interest. A few Seyferts were included and a number of other bright-nucleus galaxies showed infrared emission at longer wavelengths. Those with "infrared excesses", i.e. redder in the K-L (2.2 – 3.4μm index) included NGC 613, NGC 1672, NGC 5253, NGC 7552, NGC 1365 and NGC 1808. Most of these are now recognized to be Seyferts. NGC 7582 and NGC 7552, members of the Grus Quartet, have strong star formation and possible Seyfert activity in their nuclei.

A second paper extended this list, showing that NGC 1808, NGC 7582 and the known Seyfert IC 4329A had strong excesses, while NGC 5236 had a weak one (Glass, *MNRAS* **175**, 191, 1976). Most of the bright galaxies that I photometered have by now been studied in great detail.

Around 1976 InSb photodiodes replaced the PbS photoconductive detectors and soon led to a considerable increase in sensitivity of the JHKL photometers, making it possible to extend observations to fainter objects.

BL Lac objects and QSOs

Many of the known examples of these were too faint to be observed on the 1.9m telescope. However, certain active galaxies were being monitored at 13cm and 6cm wavelengths in the radio at HartRAO, including AP Lib and PKS 0537-441, a QSO with redshift 0.9. In 1979, we published infrared, photographic and spectroscopic measurements of the latter, which was classified as a BL Lac object on account of its variations at al wavelengths measured. We were able to make an optical identification with an object having V = 16.2. (See G.D. Nicolson, I.S.

Glass, M.W. Feast and P.J. Andrews, “The BL Lac object PKS 1144-379”, *MNRAS* **189**, 29–31p, 1979).

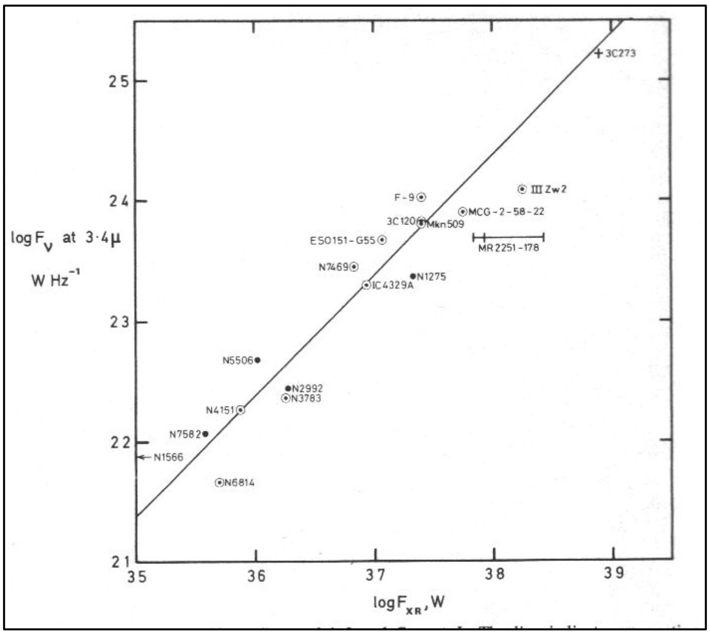
In 1978 I found that NGC 5506, a galaxy that had been identified as a strong x-ray emitter, with a bright nucleus, dust lanes and [FeII] and FeVII] emission, was very bright in the infrared, resembling a Seyfert galaxy (*MNRAS*, **183**, 85–87p, 1978). I called it “an almost Seyfert”. In fact, it has since proved to be a Seyfert.

High-z QSOs

Two z>3 QSOs, PKS 2126-15 and Q 0420-288 were observed at JHK. At this redshift, the rest-frame visible spectrum is shifted into the JHK region, far beyond the normal range for “k(redshift)-corrections”. The observed slope was appropriate for the red-shifted strong emission-line spectra of low-z QSOs. (*MNRAS* **192**, 37p, 1980).

Colours of Active Galaxies. The infrared/X-ray correlation

A series of papers dealt with general properties of active galaxies in the infrared colour-colour diagrams (J-H, H-K) and (H-K, K-L). *In Infrared observations of active southern galaxies and QSOs* (*MN* **186,** 29p, 1979), some 18 active galaxies, 11 of them known Seyferts, and 4 QSOs were also studied. They were interpreted as having colours characteristic of power laws with f_ν = Constant × $\nu^{-1.5}$, mixed with some ordinary galaxy components. Many of the (apparently, at the time) non-Seyferts such as NGC 2992, NGC 5505, NGC 7582 and Pictor A, were afterwards shown to be Seyferts.



One of the most interesting conclusions of this paper was that the X-ray flux in the 2-18 keV range was well correlated with the L-band (3.4μm) flux. This was a confirmation of some earlier work by Elvis et al *MNRAS* **183**, 129, 1978 and showed that the mechanisms involved had to be closely related.

Fig1. Correlation of 3.4μm infrared and 2-18keV x-ray fluxes in active galaxies. (*MNRAS* **186**, 29P, 1979)

Early Observations of Fairall 9

When the ESO and SRC southern sky surveys appeared, A.P. Fairall of the University of Cape Town examined about 150 southern galaxies for evidence of very high surface brightness or star-like nuclei (Fairall, *MNRAS* **180**, 391, 1977). Martin, Penfold and I obtained spectra, UBV and JHKL photometry of three of these, demonstrating that F 51 and F 9 are Seyfert I galaxies. In particular, the nucleus of F9 was shown to be particularly luminous and essentially a Quasar (Martin, Penfold & Glass, *MNRAS*. **184**, 15P, 1978). Fairall 9 (see below) subsequently turned out to be of particular interest and its variations provided a strong confirmation of the "Unified Model" for active galactic nuclei. Interestingly, repeated UBV observations of F9 had already showed evidence for variations, but the JHKL observations of that time period did not seem to.

A general paper on a number of bright QSOs and BL Lac objects showed that most had colours tending towards the power-law locus in the J-H, H-K diagram. Some showed obvious underlying galaxy contributions *MNRAS*, **194**, 795, 1981.

Colours and spectral distributions of Seyfert 1 and narrow-line X-ray Galaxies

In this work, done during my year at ESO, many of the sample were observed at longer wavelengths with the ESO infrared photometer on the La Silla 3.6m, enabling the acquisition of long-wavelength data in narrow bands (8.3μm, 9.4μm and 12μm). This enabled us to check for silicate absorption at 9.7μm, as expected if emission from dust was a major contributor. The results were interpreted as nuclei with power-law spectra added to the colours of underlying "normal" galaxies, sometimes with substantial reddening. A few indeed showed significant silicate absorption (Glass, Moorwood & Eichendorf*, A &Ap* **107**, 276, 1982).

Galaxies showing strong star formation

NGC 5253

This is a peculiar S0 galaxy showing an extended HII region complex and a strong infrared source. The infrared flux at longer wavelengths, together with the weak radio and x-ray fluxes, suggested that recent star formation had occurred. (Moorwood & Glass, *A & Ap,* **115**, 89, 1982.)

NGC 5102 and NGC 1510

NGC 5102 (S0) and the dwarf elliptical NGC 1510 are galaxies with abnormally blue colours in the visible region. Their blueness is explained by the admixture of a young population to the normal colours of elliptical galaxies. Their U-B vs V-K colours were plotted on a simple model by Struck-Marcell and Tinsley (*ApJ* **221,** 562, 1978) and are adequately represented by star formation events involving of order 10% of their masses 5 x 10^8 and 10^8 years ago respectively (Glass & Moorwood, *Observatory*, **104**, 231, 1984).

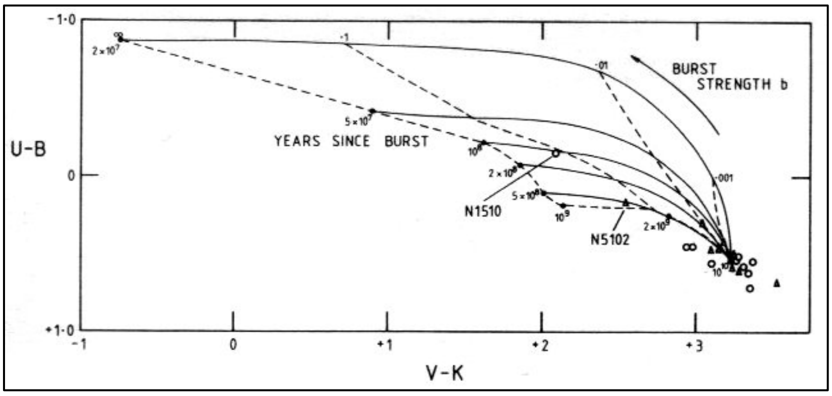


Fig 2. Diagram due to Struck-Marcell and Tinsley (1978) showing the effect of adding a starburst to the colours of a normal elliptical galaxy. Points for the two galaxies discussed have been plotted.

General view of "ordinary" and other galaxy colours in the near-IR

In order to form a base against which "active" galaxies could be compared, it was desirable to measure a large sample of "ordinary" galaxies using the same photometric system (*MNRAS* **211**, 461, 1984). Included were 19 ellipticals, 10 lenticulars, 29 spirals and one Im. The ellipticals were found to have the tightest distribution on the J-H, H-K diagram. Late-type spirals tended to be slightly bluer in J-H and those showing some emission line activity tended to be redder in H-K. In general, there is a progression of slightly decreasing J-K colour with T class (position along the Hubble Sequence). No evidence was found of colour change with aperture size, though the data were somewhat limited in this regard.

A paper entitled "JHKL properties of emission-line galaxies" (Glass & Moorwood *MNRAS* **214,** 429, 1985) compared the colours of Seyfert 1, Seyfert 2 and HII region galaxies to those of the "ordinary" galaxies above (In general, the L fluxes of ordinary galaxies were too weak to observe satisfactorily).

The discussion is in terms of the J-H, H-K and H-K, K-L diagrams for each class. Models of "Ordinary Galaxy" with black-body and power-law admixtures were presented for each diagram. Points for each galaxy were plotted on the Struck-Marcell & Tinsley (1978) diagram previously mentioned. The Seyfert 2 galaxies tended to be in between the Seyfert 1 and HII galaxies. (The HII galaxies show evidence for recent star formation.)

IRAS Survey and Seyferts

Seyfert Galaxies in the IRAS Survey (*MNASSA* **44**, 60, 1985). Various classes of galaxies for which I had photometry were searched for in the IRAS Catalog. Of course, the effective aperture of IRAS was quite large, so the fluxes represented essentially the whole galaxy rather than its nucleus. Nevertheless, some interesting facts emerged. The 1μm to 100μm spectral index, ignoring the intermediate wavelengths, did not depend much on the type of galaxy or its activity. In effect, the 1μm radiation is dominated by the stars of the underlying galaxy while the 100μm flux arises from ordinary interstellar dust. The Seyferts however have a hotter component related to the active nucleus that shows up at the intermediate wavelengths. (An abbreviated version of this appeared in *Light on Dark Matter*, First IRAS Conference, Noordwijk, The Netherlands, 10-14 June 1985 Reidel, 1986, 487–488).

Optical and near-infrared observations were made of galaxies detected by IRAS (Moorwood, Véron-Cetty and Glass *A&Ap* **160**, 39, 1986; A&Ap **184**, 63 1987). Here galaxies with Hα measurements were used to estimate star and dust formation rates and the detection rate by IRAS was about as expected.

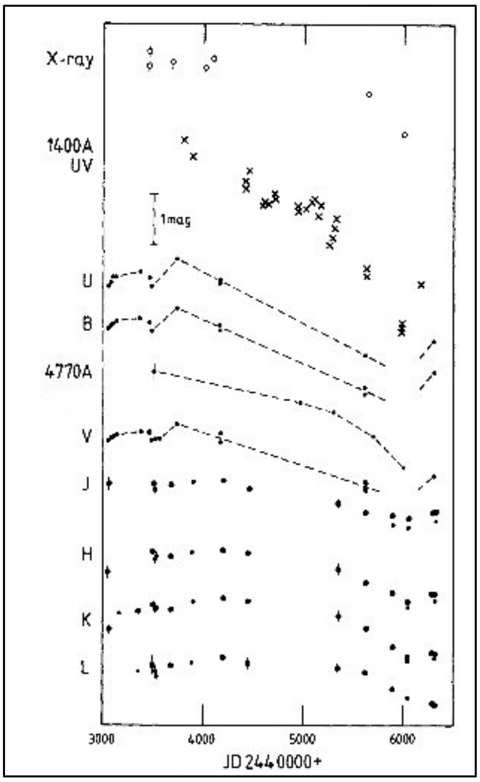
Long-term Infrared photometric monitoring of active galaxies

By 1981 I had accumulated multi-epoch data for 24 Seyfert and narrow-line x-ray galaxies. In a first paper about long-term results of this programme (*MNRAS* **197**, 1067, 1981), the positions of the galactic nuclei on two-colour diagrams were discussed and compared to models consisting of mixtures of "ordinary" (inactive) galaxies and power-law or cool black-bodies.

It was evident that variability was common among the galaxies of the sample.

The correlation of x-ray and infrared fluxes in active galaxies was again commented on.

Fairall 9 – Confirmation of the Dust Torus model



Almost immediately after its discovery, the Seyfert galaxy Fairall 9 was suspected of variability (Martin, Penfold & Glass, op cit). Several observers reported variations in the visible region . More remarkably, Morini et al (*ApJ* **307**, 486, 86) had found that its UV flux had declined by 4 mag between 1980 and 1986. Meanwhile, since 1976 I had been monitoring this galaxy at JHKL and Wamsteker et al (Proc 4th European IUE Conf, ESA SP-218, 97) had been monitoring it frequently with the IUE satellite.

*Fig3. Observations of F 9 from MNRAS **119**, 5p 1986).*

What was particularly striking was that the K and L fluxes reached their maxima well after the UV fluxes had begun their decline and that when the UV flux began to recover, the L-band lagged behind. This suggested that there was a lag of order a year between the UV output of its nucleus and the heating of circumnuclear dust. (see Variations of the Seyfert Galaxy Fairall 9, *MNRAS* **119**, 5p 1986).

In November 1987 I visited the ESO tracking station at Villafranco del Castillo outside Madrid to confer with Willem Wamsteker and Jean Clavel about a joint paper on F9.

This resulted in “Hot Dust on the Outskirts of the Broad-line Region in Fairall 9” (Clavel, Wamsteker & Glass, *ApJ*, **337**, 236, 1989) in which a strong case was put forward, using cross-correlation calculations, that the infrared flux followed the UV with a delay of 400±100 days. In other words, a torus or shell of dust is located at 400 light-days radius from the UV source. The dust, probably graphite, sublimates at a temperature of ca 1500-1700° under the influence of the UV heating. This behavior was modeled by Barvainis *ApJ* **320**, 537, 1987. Undoubtedly the dust geometry in F 9 is distributed in a favourable way so that is a clearer delay signature than is seen in most galaxies.

The spectral shape of the UV was found to stay remarkably constant, independent of its flux level.

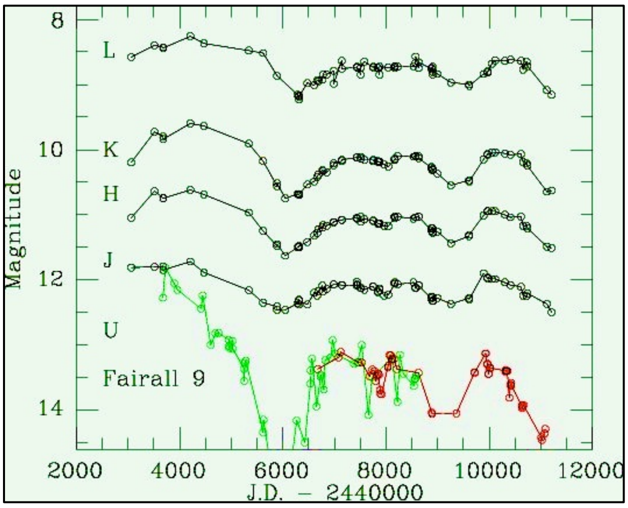


Fig 4. Summary of all the photometric data available on F9 at the end of the long-term monitoring programme. The UV data are a hybrid of IUE (coded green) and ground-based data (see MNRAS ***350****, 1049, 2004 below). UBVRI photometry was obtained by Winkler et al (MNRAS* ***257****, 659, 1992) and Winkler (MNRAS* ***292,*** *273,1997) as well as by several other observers*

The delay was confirmed by later data (see diagram and Glass *MNRAS* **350**, 1049, 2004 below).

Visible-region monitoring and Flux Variation Gradients

Variability studies of Seyfert galaxies using broad-band visible-region photometry were conducted by Winkler, Glass, van Wyk, Marang, Jones and Sekiguchi (*MNRAS* **257**, 659, 1992) over a period of four years.

Very striking is the fact that the ratios of the nuclear fluxes at the different wavelengths remain constant, indicating that the spectral shape of the variable part stays constant. This effect was first commented on by Chołoniewski (*Acta Astr* **31**, 293, 1981) and was here expanded to a much larger sample. The flux ratios derived from flux-flux ratios at different wavelengths we denote as “Flux Variation Gradients”

Final Result of the Long-term monitoring programme

This was published as "Long-term infrared photometry of Seyferts" *MNRAS* **350**, 1049, 2004. *Almost all members of the sample showed variability* at some time during the monitoring period. In some cases, this was quite dramatic. The amplitude usually increased towards long wavelengths, partly as a result of constant background galaxy contributions at the shorter wavelengths and partly because of interstellar extinction in the galaxies themselves that hid the nuclear component at shorter wavelengths.

NGC 1566 was usually fairly constant as its nucleus does not dominate the underlying galaxy in the JHKL region but some variability was nevertheless seen, mainly in the L band.

Sample long-term light curves

Some of the results from the long-term monitoring programme are shown here:

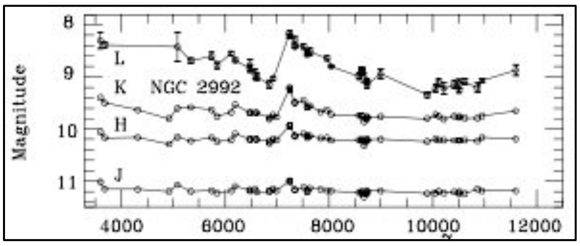


Fig 5. NGC 2992. This galaxy showed a huge outburst, especially noticeable in the L-band, around JD2447200. This outburst exceeded the normal energy expected from a supernova. It may have been in an obscured region, given its evident red colour. NGC 2992 shows evidence in the radio region for a violent superwind. (MNRAS ***292****, L50, 1997).*

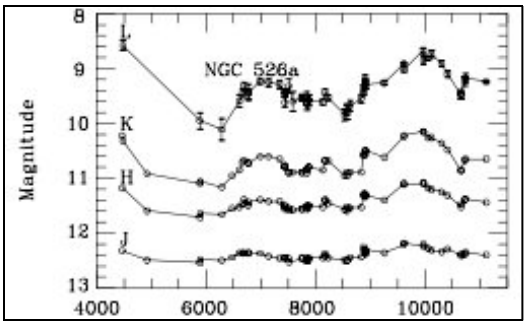


Fig 6. NGC 526a, a Seyfert 2 /Narrow Emission-line type showing large variations.

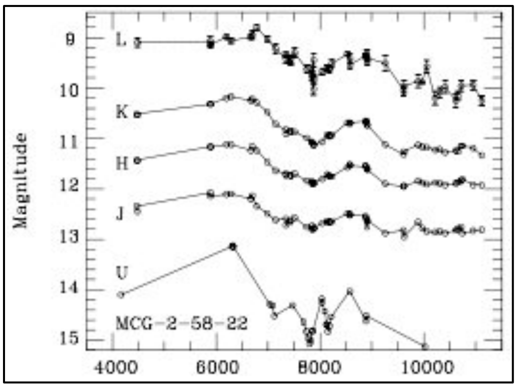
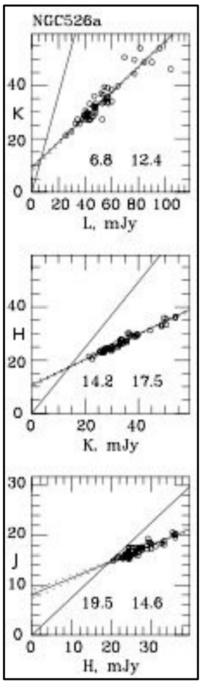


Fig 7. MCG-2-58-22, a Seyfert 1 originally identified from its x-ray output. Its U flux became too faint to observe towards the end of the series.

Flux Variation Gradients and what they reveal



Flux-flux plots were made for each galaxy and, as is the case with UBVRI photometry (Winkler et al, op cit), they are fitted well by straight lines, indicating that the flux distribution of the variable component does not change with intensity.

Fig 8. Flux-flux plots for NGC 526A. The top diagram shows K vs L, the middle one H vs K and the bottom one J vs H, all in mJy.

In each plot the (relativistic) k-corrected colours of ordinary galaxies without any allowance for extra components are plotted as lines through the origin. Linear fits have been made to the flux points for each pair of wavelengths and the slopes of these lines are the *flux variation gradients.*

The points at which the lines intersect are where is no contribution besides stars to the flux from the active nucleus, only the underlying galaxy being present. That is, the active nuclei are then quiescent.

In this particular example (NGC 526A) the underlying galaxy has fluxes at J,H of (14.6, 19.5), at H,K of (17.5, 14.2) and at K,L of (12.4, 6.8) mJy. As can be seen, the fluxes of the underlying galaxies agree approximately from one wavelength region to the next but the agreement is limited by the possibility that the underlying galaxies may not be truly “ordinary”, i.e. that they have other constant non-variable nuclear constituents besides stars.

In reality it can be expected that many active galaxies will have dust and/or HII region components with emission lines that will affect their colours.

General Properties of the Flux Variation Gradients

The flux variation gradients can be readily be converted into infrared colours and plotted in a histogram.

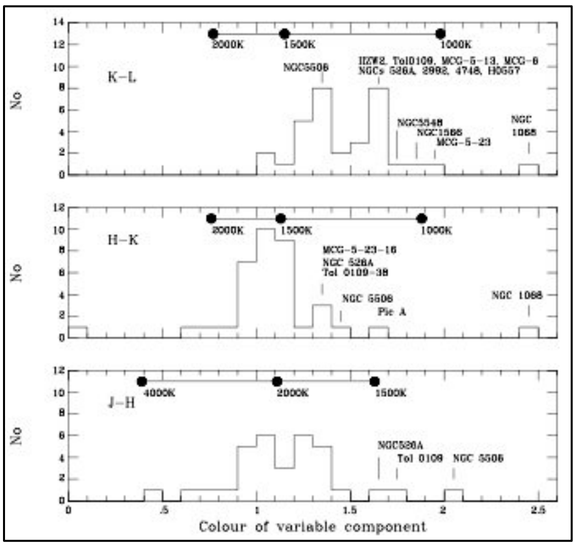


Fig 9. Distributions of the colours of the variable components of Seyfert galaxies derived from the Flux Variation Gradients.
In each case the theoretical colours for black-body at various temperatures are also shown. From Glass, MNRAS **350**, 1049, 2004.

The H-K colours typically correspond to temperatures of around 1500K, at which dust particles probably sublimate.

These diagrams suggest that the K-band (2.2μm) spectral region is dominated by the hottest (innermost) part of the dust shell at about 1500°. Evidently, at higher temperatures, dust cannot exist and is sublimated. Quite likely, the L band is affected by cooler dust components that lie further from the nucleus. On the other hand, the J-H colour is probably a composite of the short-wavelength tail of the dust emission and by the long-wave tail of the exciting source in the nucleus.

It is further noticeable in this diagram that the Seyfert 2 galaxies have redder colours than the Seyfert 1s, presumably due to reddening by their greater interstellar dust content.

Cross-correlation results - delays

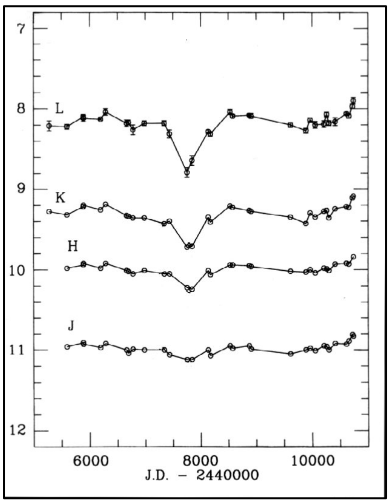
After the early result that there was a clearly-defined lag between the UV variations and the infrared response in F 9, all objects in the long-term monitoring programme were examined for delays between the shortest and longest-wavelength photometry.

Because of the sampling interval, usually either a few days or about 3 months, the most reliable delays are likely to be those with variations that are smooth on a time-scale longer than this. That is to say, the more luminous galaxies in general.

It should be noted that the cross-correlation of irregularly-spaced data is controversial and inherently imperfect. Some of the likely problems were discussed in the Long-term Monitoring paper (*MNRAS* **350**, 1049, 2004).

Studies of particular Seyferts

NGC 7469 (*MNRAS* **297** 18 1998)



This Seyfert 1 galaxy has a well-defined circumnuclear star-forming ring of about 4" diameter. Around October 1989 there was a sudden dip in the nuclear flux from this galaxy, also observed in visible-region broad-band photometry and the broad component of the Hβ emission line also disappeared (see refs in the above article). This behavior was unique amongst the galaxies observed by me.

A supernova was detected near the nucleus of this galaxy in 2000, unfortunately after the end of the infrared observations.

Fig 10. Light curves of NGC 7469 showing the unusual dip in its nuclear output around October 1989.

In the H/K flux-flux diagram for NGC 7469 I show the effect of shifting its origin to allow for the presence of a constant component from the circumnuclear ring, estimated from Genzel et al (*ApJ* **129,** 444, 1995). The observed infrared fluxes thus are the sum of the ring, ordinary galaxy and variable components.

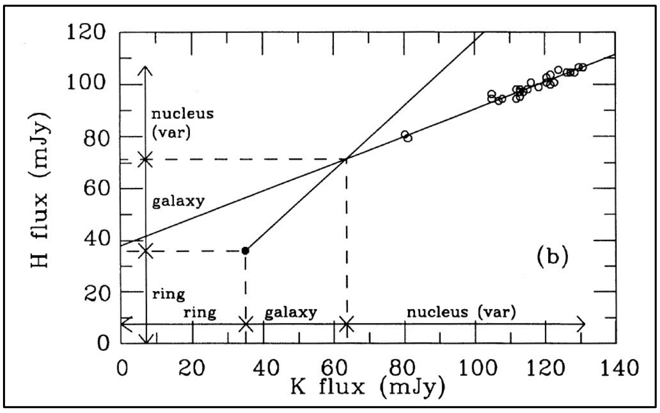


Fig 11. H/K flux-flux diagram for NGC 7469. The ring contributions were estimated from Genzel et al (op cit).

Observations were also made at L by Marco and Alloin in August 1996 (A&Ap 336, 823, 1998) with an adaptive optics system, concluding that about 36% of the flux at K is in the ring component and about 55% of that at L arises from the core. My estimate of the L component was about 50 mJy from the ring component and 80 to 120 mJy from the core and underlying galaxy combined.
NGC 3783

In "IR variability of the Seyfert galaxy NGC 3783" *MNRAS* **256**, 23p, 1992 a delay of 80-90 days was found between the UV and the infrared but the later result found in *MNRAS* **350**, 1049, 2004 suggested a much longer delay of around 185 days. This disagreement is probably due to the poorer sampling interval in the latter case. A paper by Lira et al *MNRAS* **415**, 1290, 2011 with much better sampling suggests that 60-80 days is appropriate.

NGC1068

The archetype Seyfert 2, **NGC 1068**, showed a steady, smooth, rise in its near-infrared output over many years, but afterwards began what looks like an equally steady decline (*MNRAS*, **276**, L65, 1995). For connection with H_2O maser activity, see Gallimore et al *ApJ*, **556**, 694, 2001.

Large Collaborations

In addition, I contributed measurements to the following large collaborations:
NGC 4593, conf,
NGC 5548 ApJ 366, 64, 1991 (~500 citations!)
NGC 1566 A&Ap, 256, 375, 1992,
NGC 3783 ApJ, 425, 609, 1994. collaboration
PKS 2155-304 ApJ, 438, 120, 1995, 438, 108, 1995
NGC4593, MNRAS, 270, 580, 1994, MNRAS 274, 1, 1995
3C279 ApJ, 435, L91, 1994, ApJ, 459, 73, 1995
NGC 4151 ApJ, 470, 322, 1996, ApJ 470, 364, 1996
PKS 0528+134 A&Ap 348, 63, 1999
PKS 2005-489 A&Ap 368, 38, 2001