Ultraluminous Infrared Galaxies

I.F. MIRABEL, Service d'Astrophysique, CEN-Saclay, France

The Infrared Astronomical Satellite (IRAS) revealed a class of luminous galaxies that emit almost all the energy (≥95%) in the far-infrared. The most extreme galaxies of this type radiate as much as $10^{12} L_{\odot}$ in the 8 μm–1000 μm wavelength band, which is equivalent to the accepted minimum bolometric luminosity of quasars. These objects are called "ultraluminous infrared galaxies". Although the space density of ultraluminous infrared galaxies exceeds that of optically selected quasars of the same bolometric luminosity, there are only a few tens of galaxies of this type in the Local Universe ($z \leq 0.13$).

The study of "luminous infrared galaxies" has now become a key area in extragalactic research for two reasons: (1) We have come to the realization that above $10^{11} L_{\odot}$ the infrared luminous galaxies are the dominant population of objects in the Universe, being as numerous as Seyferts, and more numerous than quasars of the same bolometric luminosities[1]. (2) There is increasing evidence that luminous infrared galaxies may represent an early and brief phase in the evolution of galaxies, and that their study will provide clues for our understanding of the genesis of the most energetic – quasars and radio galaxies – and most massive – giant elliptical galaxies – in the Universe.

Most of the far-infrared emission from galaxies is due to the absorption and re-emission of light by dust. Although the luminosity density in the Local Universe seems to be evenly split between cool disk emission and warmer starburst emission, from the IRAS colours we know that the infrared emission from ultraluminous infrared galaxies is mostly radiated by warm dust. At present it is not known if the source of the light that heats the dust consists solely of large amounts of massive stars, or if in addition, the formation of gigantic black holes with X-ray emitting accretion disks are also required to explain the colossal amounts of thermal energy radiated by the dust in the far-infrared.

To reveal the nature of the host galaxies and to understand the origin of the greatly enhanced infrared radiation, we are carrying out at ESO, optical, infrared and radio observations of a flux limited sample of the nearest luminous infrared galaxies, selected from a survey[2] of bright IRAS galaxies in the southern hemisphere.

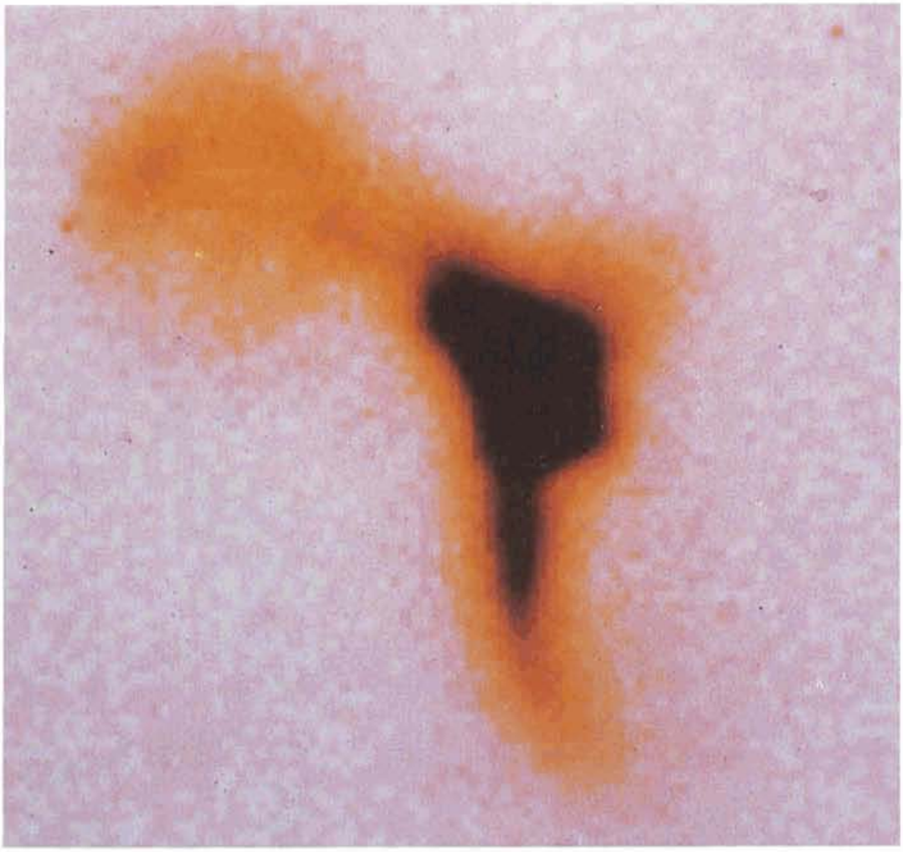

Figure 1: *R band CCD image of the "South America" galaxy obtained with the NTT. This galaxy is receeding from the Sun at 23,200 km s^{-1} and radiates 10^{12} solar luminosities in the far-infrared.*

NTT Images

The optical morphology of ultraluminous infrared galaxies has recently been a subject of controversy. Whereas from observations with the Palomar 1.5-m telescope some authors[3] had concluded that nearly all ultraluminous infrared galaxies are strongly interacting mergers, from studies at La Palma, other authors[4] conclude that galaxy interactions are far from being an ubiquitous factor among this type of galaxies. In view of the contradictory reports on the morphology of ultraluminous infrared galaxies, optical imaging with the most advanced technology had become necessary. The excellent optics of the New Technology Telescope (NTT) and the good seeing conditions on La Silla were fully exploited to arbitrate on the question of the optical morphology.

CCD images of the 16 nearest ultraluminous infrared galaxies in the southern hemisphere[5] were obtained using the second ESO Faint Object Spectrograph and Camera (EFOSC2) attached to one of the Nasmyth focii of the NTT. The observations were carried out during the commissioning period of these instruments. The detector used was a low resolution (320 × 512,30 μm pixels) RCA CCD. The exposures were obtained through a Bessel R filter. Typical exposure times were of 2 minutes. The diameters of stellar images on these exposures allowed the resolution of faint features with sizes ≥ 2.5 kpc, for this nearby sample ($z \leq 0.13$) of objects.

A clear result from the NTT images is that none of the sample galaxies show either the spiral or the elliptical shapes that are characteristic of isolated galaxies. On the contrary, the NTT images reveal a wide variety of morphologies that can be interpreted as resulting from gravity in strongly interacting merger systems (e.g. Fig. 1). Tails, bridges and/or double nuclei are apparent in all galaxies $cz \leq 25{,}000$ km s^{-1} (e.g. Fig. 2). However, in the images of galaxies at higher redshifts, the faint extended features that are characteristic of tidal interactions are less ostensible, and become increasingly blurred with increasing distance.

From the detailed optical inspection of the 16 nearest ultraluminous infrared sources made with the NTT it is concluded that ultraluminous infrared galaxies are colliding galaxies that have profoundly penetrated each other. In fact, we find a critical separation of

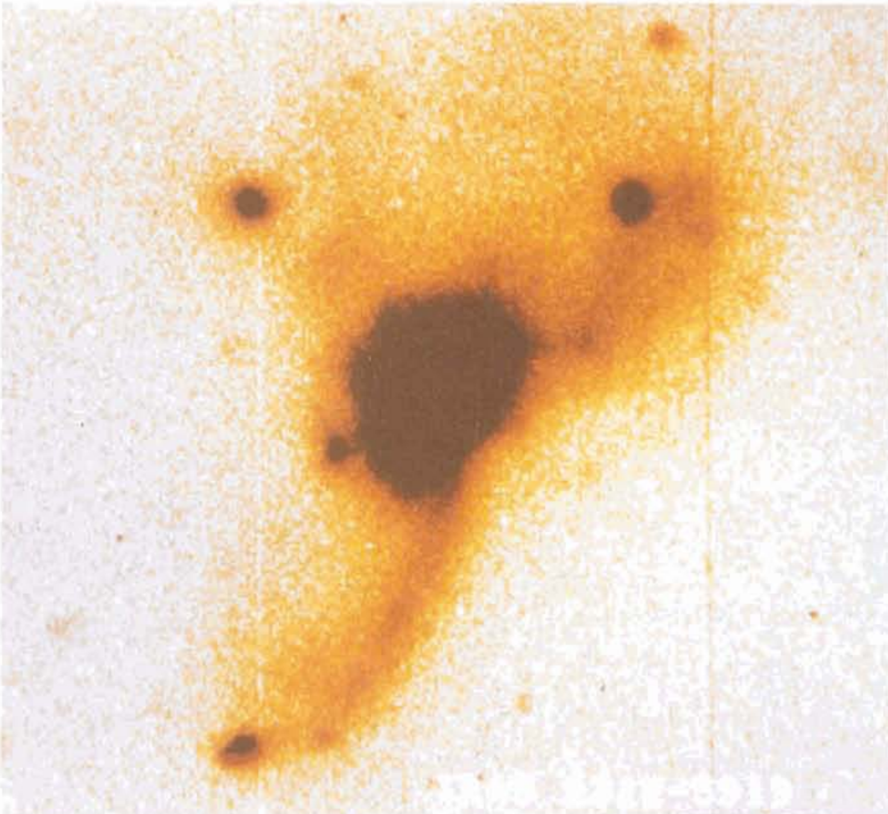

Figure 2: *R band CCD image of the galaxy IRAS 23128-5919 obtained with the NTT. Computer simulations show that the elongated features emanating from the central object are the result of tidal interactions between merging disk galaxies. At the distance of IRAS 23128-5919, the condensations seen at the end of the tails would have the luminosities of star forming dwarf galaxies.*

about 10 kpc between the nuclei of the colliding galaxies (e.g. Fig. 3). In other words, advanced merging seems to be a necessary condition for the greatly enhanced infrared luminosity.

SEST Observations

Since cold interstellar gas is the fuel for intense massive star formation, studies of the molecular gas in IR luminous galaxies are important for our understanding of the ultimate source of the energy radiated by these systems. The Swedish programme committee allocated the observing time needed to carry out a survey of the $CO(1 \rightarrow 0)$ emission from an IRAS flux limited sample of 33 galaxies with $L_{IR} \geq 10^{11} L_{\odot}$. $CO(1 \rightarrow 0)$ emission was detected from most of the galaxies of this sample up to a redshift of 0.1[6],[7].

From the SEST observations it was found that IR luminous galaxies are extremely abundant in turbulent CO. The emission profiles show velocity widths of up to 1000 km s^{-1} (e.g. Fig. 4). Using a galactic $CO \rightarrow H_2$ conversion factor one derives total masses of H_2 in the range of 6-60 10^9 $M_{\odot}$, namely 2-20 times the mass of molecular gas in the Milky Way. The infrared luminosities per nucleon of molecular gas, $L_{IR}/M(H_2)$, are in the range of 10-80 $L_{\odot}/M_{\odot}$. This is 5-40 times the global value of this ratio in the Galaxy averaged over the hole disk. This ratio is also larger than the average ratio found in starburst galaxies like M82. From the NTT and SEST observations it is then concluded that luminous infrared galaxies represent colliding, and in the most extreme cases, mergers of giant gas-rich galaxies.

In deriving H_2 masses from the $^{12}CO(1 \rightarrow 0)$ emission one should keep in mind that there may be systematic biases that depend on the physical properties of the molecular gas, such as the mean temperature, density, and metallicity. To study the physical properties of the molecular gas in luminous infrared galaxies, $CO(2 \rightarrow 1)$ and ^{13}CO observations of the five brighter galaxies were carried out. The analysis of these observations will provide an important test of the use of the galactic $^{12}CO \rightarrow H_2$ conversion factor in this type of galaxies.

Infrared Observations

One of the most relevant questions that remain open about these intriguing systems is if in addition to bursts of massive star formation, compact non-thermal sources (AGN) are really needed to produce the extraordinary infrared luminosities above $10^{12} L_{\odot}$. Because of heavy optical obscuration along the line of sight to the central regions, infrared imaging is one observational approach to this question.

Observations with IRAC in the J(1.25 μm), H (1.65 μm), K (2.2 μm), and L(3.6 μm) will be conducted in the near future. Imaging in the N(10 μm) band is also planned with the TIMMI camera being constructed at CEN-Saclay under contract with ESO. These infrared observations will substantially improve our knowledge of the central morphology of these galaxies. Through the large amounts of obscuring dust they may be able to reveal the presence of multiple nuclei. Furthermore, the infrared colours will provide essential information to discriminate between different components of the central energy source, namely, starlight from red supergiants formed during super-starbursts, thermal emission from hot dust, and possible emission from an accretion disk surrounding an AGN. By comparing the ratio of the 10 μm to thermal radio emission found in the central regions of ultraluminous infrared galaxies, with the ratio found in galactic H II regions we will test the controversy "Starburst-AGN's".

Optical Spectroscopy

Low and high dispersion optical spectroscopy of the 20 most luminous objects at $z \leq 0.13$ was carried out with the 4-m Tololo telescope[8]. Na D absorption lines and strong Balmer decrements are common features in the spectra of the nuclei. Despite the strong absorption, it is found that about 50% of the nuclei are Seyfert 2's, the other 50% liners or starbursts. The [O III] emission lines show asymmetric shapes with extended blue wings, that may result from an attenuation of the emission from the far side of outwardly moving line-emitting gas mixed with dust.

An interesting possibility is that merging disk galaxies may not only trigger nuclear activity, but also eject dwarf galaxies into intergalactic space. We became interested in this idea after a close inspection of the NTT images of these galaxies. Patches of luminous material usually appear at the tips of the tidal tails (e.g. Fig. 2). Another specially interesting feature is a blue knot found in the Superantennae[9] at a projected distance of 200 kpc from the merging nuclei. If these objects are actually associated to the merging disks, their luminosities are comparable to star forming dwarf galaxies.

At present we do not know why bursts

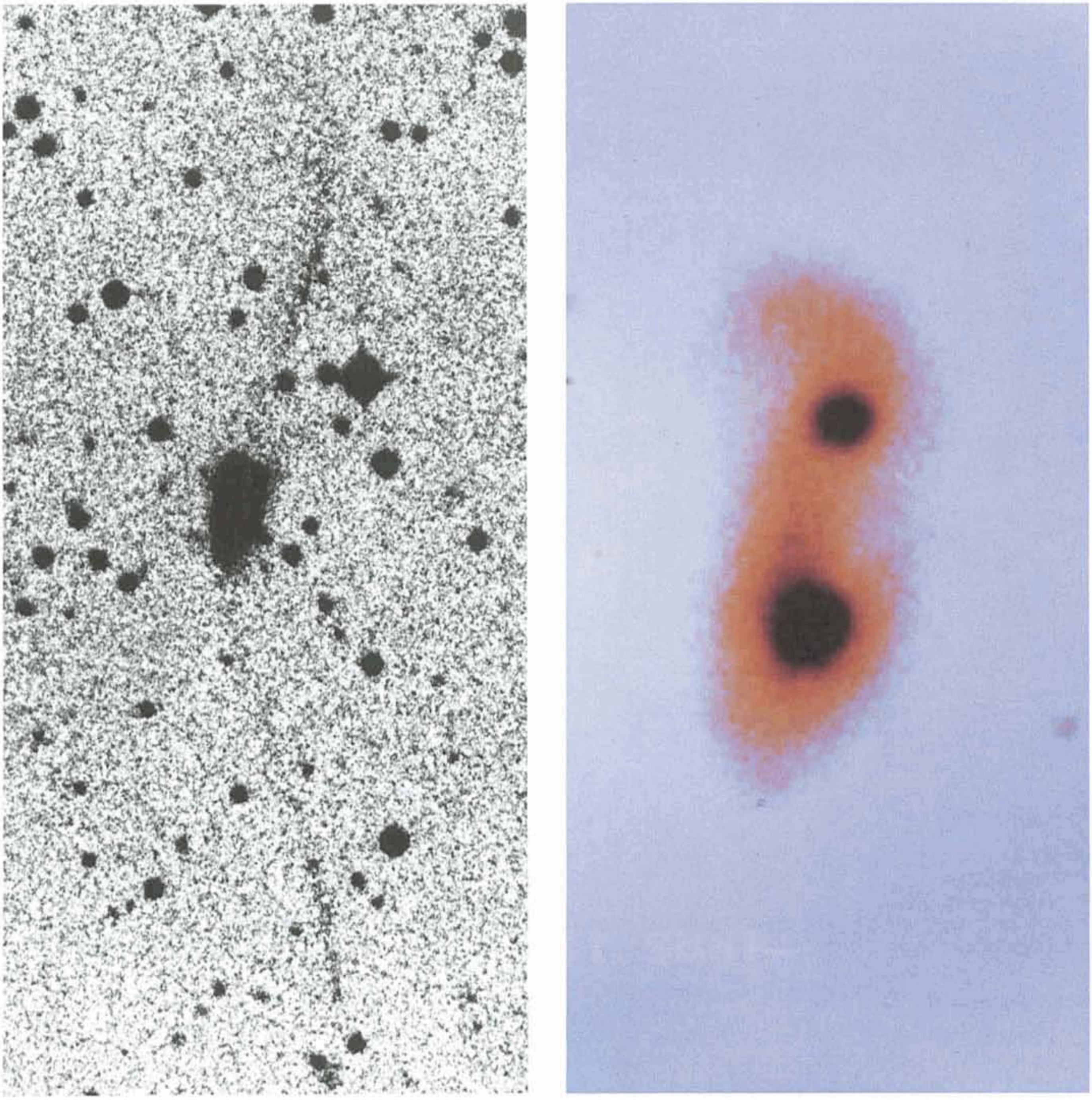

Figure 3: "The Superantennae", a remarkable galaxy at a distance of 250 Mpc[9]. The colossal tails seen in the black-and-white reproduction of an ESO survey plate stretch to an unprecedented total extent of 350 kpc. The false-colour CCD image obtained with the NTT reveals inside the central body from which emerge the gigantic tails, two galaxy nuclei separated by only 10 kpc.

of star formation should occur at the ends of tidal tails. Furthermore, it is not clear how massive stars could be formed in intergalactic space out of the scattered debris of galaxy-galaxy collisions. We have proposed to carry out spectroscopy of these condensations with EFOSC on the 3.6-m to: (1) confirm their physical association to the merging disks, (2) determine the chemical composition of the HII regions in the tidal tails, and (3) probe a mechanism that returns metal-enriched gas into intergalactic space.

The IRAS view of the sky led to the discovery of a few tens of ultraluminous infrared galaxies in the Local Universe. Since in an expanding Universe, galaxy-galaxy collisions must have been more frequent in the past, it is likely that the several hundred times more sensitive Infrared Space Observatory (ISO), a European space mission to be launched in the year 1993, will reveal a large population of this type of objects in earlier epochs. To look back into the history of the Universe, and to inspect in detail the directions signalled by ISO, we will need terrestrial telescopes more powerful than the NTT, telescopes like the 16-m Very Large Telescope to be installed in Chile by ESO.

References

[1] Soifer, B.T., Sanders, D.B., Madore, B.F., Neugebauer, G., Danielson, G.E., Elias, J.H., Lonsdale, C.J., Rice, W.L. 1987, *Astrophys. J.* **320,** 238.

[2] Sanders, D.B. and Mirabel, I.F. 1991, in preparation.

[3] Sanders, D.B., Soifer, B.T., Elias, J.H., Madore, B.F., Matthews, K., Neugebauer,

G., Scoville, N.Z. 1988 *Astrophys. J.* **325,** 74.
[4] Lawrence, A., Rowan-Robinson, M., Leech, K., Jones, D.H.P., Wall, J.V., 1989, *Mon. Not. Roy. Astr. Soc.* **240,** 329.
[5] Melnick, J. and Mirabel, I.F. 1990 *Astron. Astrophys.* **231,** L19.
[6] Mirabel, I.F., Booth, R.S., Garay, G., Johansson, L.E.B., Sanders, D.B. 1988, *Astron. Astrophys.* **206,** L20.
[7] Mirabel, I.F., Booth, R.S., Garay, G., Johansson, L.E.B., Sanders, D.B. 1990, *Astron. Astrophys.* **236,** 327.
[8] Maza, J. and Mirabel, I.F. 1991, in preparation.
[9] Mirabel, I.F., Lutz, D., Maza, J. 1991, *Astron. Astrophys.* in press.

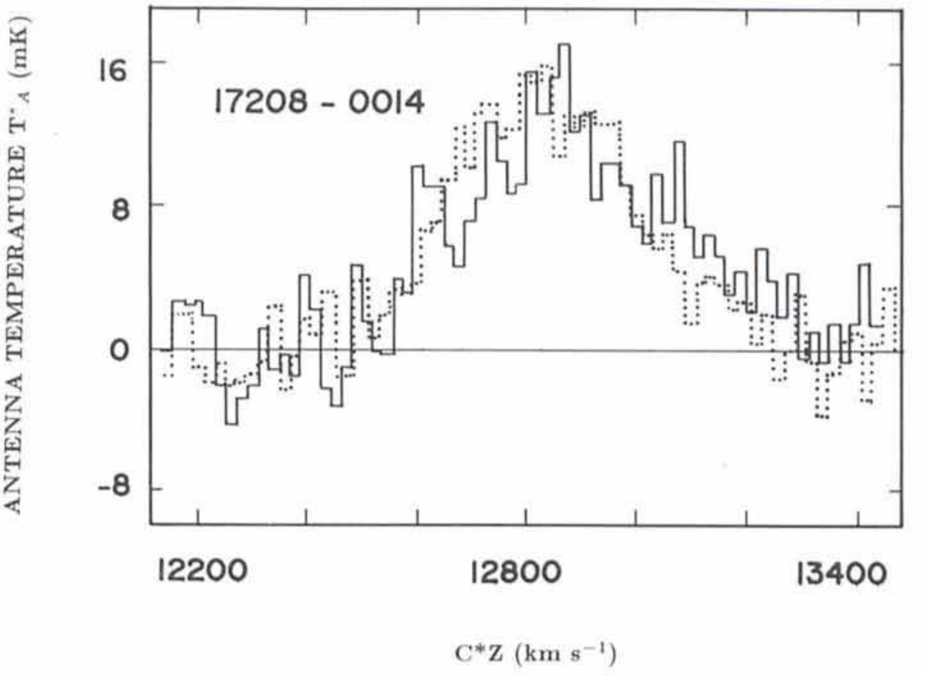

Figure 4: *CO(1→0) emission profile of an ultraluminous infrared galaxy as observed with SEST (solid line) and the NRAO 12-m telescope (dotted line). This type of observation shows that luminous infrared galaxies are extremely rich in interstellar molecular gas.*

Blue Galaxies in the Field of the Quasar PKS0812+02

E. GIRAUD, ESO

1. Introduction

Some galaxy clusters at z=0.3–0.4 have a higher frequency of galaxies with signs of recent star formation or nuclear activity than their nearby counterparts. The most luminous red galaxies in these clusters, however, do not show any evidence of evolution. At higher redshift (z=0.7) there seems to be a significant variation in the 4000Å break amplitude of the reddest galaxies (Dressler, 1987; see also Giraud, 1990), suggesting that evolution of the most passive galaxies has also been detected.

Low-redshift quasars (z≤0.4) are not found in very rich clusters of galaxies. Nevertheless they appear to be located in regions of higher-than-average galaxy density (Yee and Green, 1984). The environment of quasars at z~0.6 is sometimes radically different. Some of them are found in environments as rich as those of Abell class 1 clusters (Yee and Green, 1987). While at higher redshift field contamination is necessarily large, Tyson (1986) and Hitzen, Romanishin and Valdes (1991) have also reported an apparent excess of galaxies near quasar at 0.9≤z≤1.5.

These sets of observations indicate that there has been a rapid evolution of clusters in the range z=0.2 to 0.7.

The nature of the population of clusters containing quasars is not well known. Results on two of these have shown that they have a large blue population (Yee, 1988). In fact, the cluster which is apparently associated with PKS0812+02 at z=0.403 (Fig. 1) has a fraction of blue objects larger than any of the ten clusters at z = 0.3 observed so far in the GC3 programme. According to Yee, this structure is compact and centrally concentrated and has a richness between that of class 0 and 1.

Observing the population in the field of PKS0812+02 is important for the following reasons:

(a) the cluster membership has to be carefully checked since a quasar in a cluster is a rare event, and because the population in this probable cluster appears to be photometrically different;

(b) its redshift is in the range where there seems to be a dramatic evolution of clusters.

Obtaining spectra of blue galaxies is important for understanding the nature of this intriguing population.

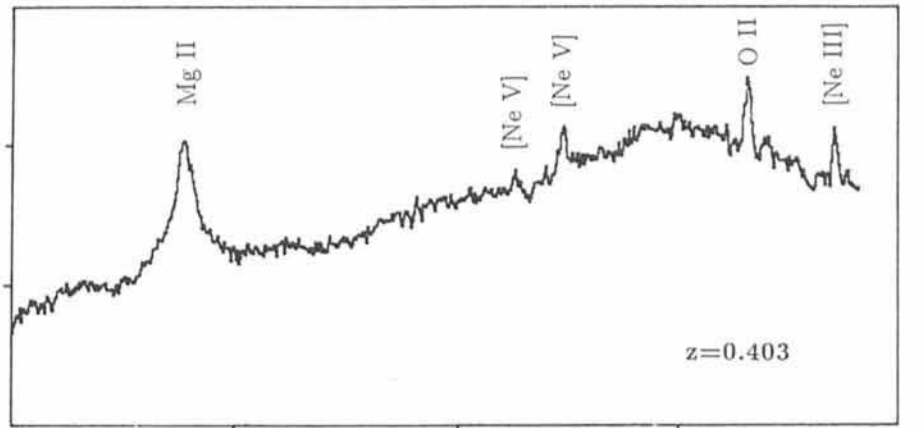

Figure 1: *A blue spectrum of PKS0812+02 obtained with the NTT and EFOSC2 at a resolution of 2Å per pixel (Grism No. 3). The observation was done to check the feasibility of blue spectroscopy with a TH CCD (January 30, 1990; exp.:1800 s).*