reduced to better than 3 % in the flat-fielded spectrum. The equivalent widths of the faintest interstellar lines recorded in the spectrum are about 40 mÅ.

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IRAS* Ground-based Follow-up at ESO

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Introduction

The InfraRed Astronomical Satellite (IRAS) was successfully launched on 26 January 1983 from Western Test Range, Lompoc, California. The satellite died when the superfluid liquid helium which kept the telescope and the infrared instrumentation at its operating temperature of a few degrees Kelvin ran out on 22 November 1983. The very good performance of the satellite, the telescope and the infrared instrumentation has surpassed most preflight expectations. Due to the excellent attitude control system IRAS source positions are generally accurate to about 20 arcseconds. The extraordinary dark current stability of the infrared detectors has made it possible to attain an overall photometric accuracy of about 10 % and has in addition enabled us to also study extended emission features in the infrared sky.

The daily avalanche of infrared data accumulated over the 300 day IRAS mission has resulted in infrared parameters of about 300,000 astronomical sources. These sources are inhomogeneously distributed over the sky, with source densities varying from about 50 sources per square degree in the galactic plane (the source confusion limit) to about one source per square degree at the galactic poles. The reduction of the IRAS data and the preparation of the IRAS point source catalogue is carried out under the responsibility of the Joint IRAS Science Working Group consisting of astronomers from the three participating countries. The IRAS catalogue is presently scheduled to come out in November 1984.

The focal plane of the 60 cm Ritchey-Chretien telescope accommodated three separate instruments:

(i) The survey array, built in the US, and consisting of eight rows of altogether 62 detectors, two rows for each wavelength band (for detector sensitivities, fields of view and wavelength ranges see Table 1), and two additional Dutch instruments:

(ii) the Low Resolution Spectrometer (LRS), a slitless spectrograph, that registered 8–23 μm spectra with a spectral resolution of about 20 of all sufficiently strong (SNR $>\sim 50$) point sources observed in the survey, and

(iii) the Chopped Photometric Channel (CPC) designed to map sources at 50 and 100 μm with higher spatial resolution (1.2 arc minutes) but lower sensitivity than the survey array.

The main purpose of the IRAS mission was to systematically survey the whole sky at infrared wavelengths. About 60 % of the total available observing time was spent on carrying out this survey which was successfully completed apart from a five degree wide gap roughly centred at ecliptic longitudes 160 and 340 degrees that was missed because of operational problems. The remaining 40 % observing time was spent on mapping about 3,000 preselected sources and areas of sky at higher sensitivity (survey array) and better spatial resolution (CPC).

Due to the survey character of the IRAS mission the scientific results cover a wide spectrum of astronomical scenery and astrophysical processes, ranging from comets to quasars and providing new insights in the evolution of the solar system, stars and galaxies. Since cosmic infrared radiation is predominantly emitted by small dust particles heated by starlight, regions of high density close to stars generally stand out most clearly in the infrared. This makes the infrared the wavelength range "par excellence" to study stars in the process of formation when they are still immersed in the gas and dust clouds from which they have formed as well as stars at the end of their lives when they have evolved to red giants and are blowing off their envelopes on a relatively short time scale ($\sim 10^5$ years) before turning into white dwarfs or exploding as supernovae.

Ground-based IRAS Follow-up

To illustrate the capabilities of IRAS compared to ground-based telescopes in the infrared, it is instructive to compare the performances at 10 and 20 μm where observing from the ground is possible but severely hampered by atmospheric emission. To reach the same limiting sensitivity as IRAS at 10 μ with the 3.6 m ESO telescope requires 200 times longer integration times (40 seconds) at 10 μm and about 30,000 times longer (2 hours) at 20 μm in spite of the fact that the collecting area of the 3.6 m is about 40 times larger than that of the IRAS mirror. For this estimate I have assumed that sources are pointlike (smaller than the 3 arcseconds diaphragm of the IR photometer). If, as for virtually all protostars and galaxies, the sources are extended, the integration times go up proportional to the area of the source. In fact, to reach the same surface brightness sensitivity as IRAS, one would have to integrate about 2,000 times longer than estimated above.

This little bit of trivial numerology shows that ground-based follow-up of IRAS sources in the infrared is only profitable at 10 μm and shorter infrared wavelengths and would greatly benefit from the availability of an array-photometer, now in use at several other major observatories in the world. The enhanced spatial resolution that one can reach from the ground makes it worthwile to have such an instrument for more detailed studies of fine-scale structure in the brightest sources detected by IRAS.

Two infrared observing runs that we had in 1983 were totally unsuccessful because of bad weather but in view of the considerations above it is doubtful in retrospect how much could have been achieved with the conventional infrared photometer presently available at the 3.6 m telescope.

* The InfraRed Astronomical Satellite was developed and is operated by the Netherlands Agency for Aerospace Programmes (NIVR), the US National Aeronautics and Space Administration (NASA), and the UK Science and Engineering Council (SERC).

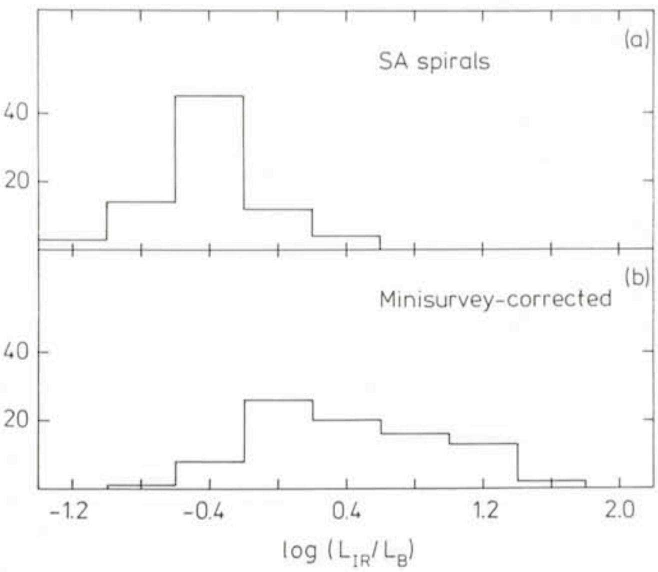

Fig. 1: *Infrared excess distributions of an optically complete (a) and an infrared-complete (b) sample of galaxies.*

Extragalactic IRAS Follow-up in the Optical

It is outside the scope of this short article to review all the exciting new discoveries made up to now by IRAS (see the 1 March 1984 issue of the *Astrophysical Journal* Letters). Instead I will concentrate on the extragalactic results and present ground-based optical spectra of galaxies with large infrared excesses recently obtained at ESO.

IRAS has detected infrared radiation of about 10,000 galaxies, the majority spirals. Most of these galaxies are optically faint (B >14), many of them so faint that they do not appear in any presently available catalogue while some do not even show up on Palomar and ESO/SRC Sky Survey plates (B >19).

Fig. 1 shows the distributions of infrared excesses of two samples of spiral galaxies, an optically complete sample (B < 12.5) and an infrared complete sample (S < 60 μm > 0.5 Jy). The former is a sub-set of the optically complete sample of Shapley-Ames galaxies analysed by de Jong et al. (1984). The infrared sample is the IRAS mini-survey sample of Soifer et al. (1984). Care has been taken to treat the optical magnitudes of galaxies in both samples in the same way by attempting to correct the magnitudes of the mini-survey galaxies for systematic errors in the adopted Zwicky magnitudes and for galactic extinction.

It can be shown that the optically complete sample is representative for the local (d ≲ 100 Mpc) population of spiral galaxies. Thus, according to the data in Fig. 1 a, spirals emit on the average about 0.4 times as much energy in the infrared as in the visible.

The infrared sample is of course biased towards large infrared excesses. Fig. 1b shows that about 60 % of the roughly 10,000 galaxies detected by IRAS emit more energy in the infrared than in the visible.

In the following I will refer loosely to galaxies which emit more than four times as much energy in the infrared as in the visible as "starburst" galaxies. Although they constitute less than 1 % of all spiral galaxies, roughly 30 % (about 3,000) of the galaxies detected by IRAS are starburst galaxies. The most extreme ones have recently been found to emit up to several hundred times more energy in the infrared than in the visible (Aaronson and Olszewski 1984).

The fraction of interacting galaxies among infrared galaxies is significantly higher than expected on the basis of random statistics suggesting that (distant) encounters between galaxies may play an important role in triggering bursts of star formation.

Most starburst galaxies identified by IRAS are astronomically speaking "terra incognita". For most of them not even magnitudes are known. In order to study these galaxies in more detail we (T. de Jong, G. K. Miley, J. Lub and R. de Grijp) have started a ground-based follow-up programme at ESO.

First we selected a sample of southern starburst galaxies from the IRAS database in a roughly 1,000 square degree area of sky between RA = 10 and 14 hrs and between Dec = −40 and −60 degrees. Of these galaxies we are presently in the process of collecting optical spectra and CCD pictures. The spectra are taken at the 3.6 m telescope with the Boller and Chivens spectrograph using the IDS detector, and the CCD pictures will be taken at the 1.5 m Danish telescope. The spectra will enable us to determine redshifts and to study the ionized gas while the CCD pictures are required to accurately determine magnitudes and to investigate the distribution of the optical emission and the galaxy morphology.

In Fig. 2 we show spectra for two galaxies, IRAS 1027-395 (MCG 07-22-019) and IRAS 1318-314 (for infrared fluxes see IRAS Circular No. 13), that we obtained during a recent observing run at ESO. The spectra show strong narrow emission lines of Hydrogen (Hα at λ 6563 and Hβ at λ 4861), Nitrogen ([N II] at λλ 6548/6583), Oxygen ([O III] at λλ 4959/5007) and Sulphur ([S II] at λλ 6716/6731). The lines are unresolved at the spectral resolution of about 13 Å, corresponding to FWHM line widths less than 600 to 800 km s^{-1}. At this resolution the lines of the Nitrogen doublet show up as shoulders in the Hα line and the [S II] doublet lines are blended together. The line ratios are very similar to those observed for a sample of galactic nuclei studied and appropriately referred to as "starburst" nuclei by Balzano (1983). The observed [O III]/Hβ ratios are characteristic for regions of ionized gas excited by massive stars.

The two galaxies for which spectra are shown in Fig. 2 have redshifts of 0.0148 and 0.054, respectively, corresponding to distances of 89 and 230 Mpc (assuming a Hubble constant of 50 km s^{-1} Mpc^{-1}. At these distances the 4″ × 4″ aperture with

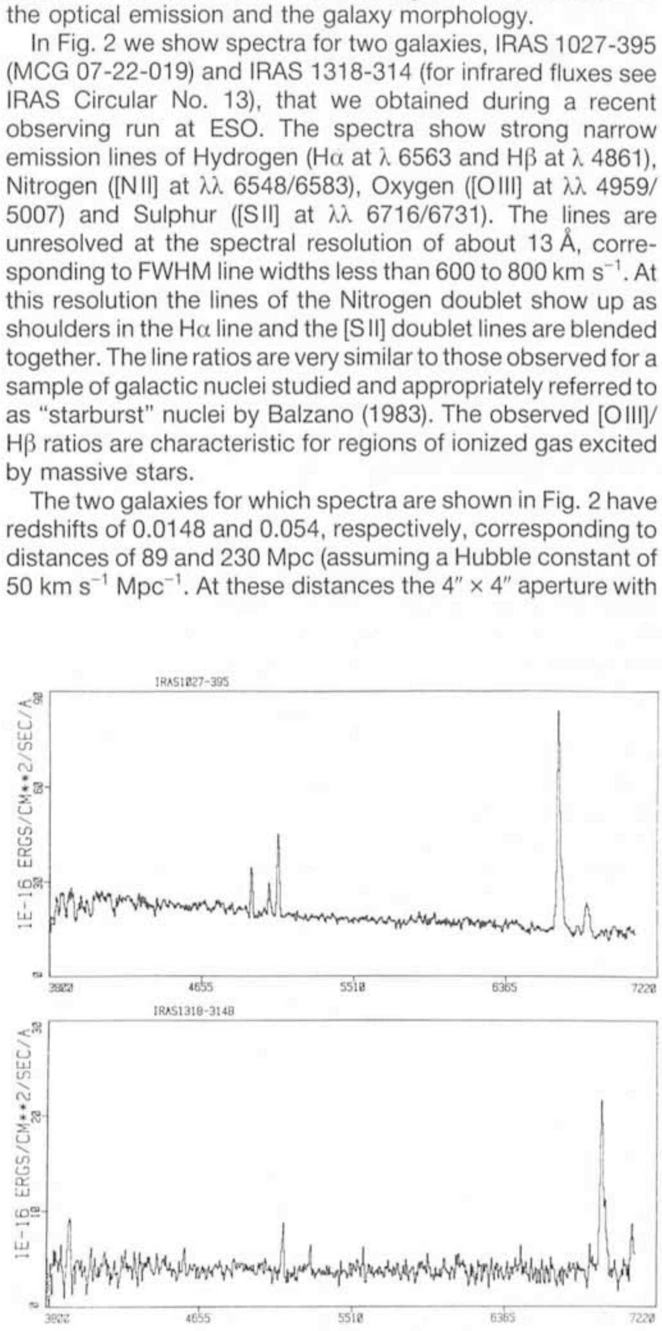

Fig. 2: *IDS spectra of starburst galaxies taken with the Boller and Chivens spectrograph at the 3.6 m telescope by J. Lub and R. de Grijp.*

which the spectra were taken, samples central regions with dimensions of 1.7 × 1.7 and 6.2 × 6.2 kpc^{-2}.

A comparison of hydrogen recombination line intensities with infrared luminosities in principle allows the determination of the masses of the stars formed in a starburst. In practice such a comparison is complicated by the fact that the field of view of the IRAS detectors is much larger (of the order of several square arcminutes, see Table 1) than the aperture used for the spectral observations. To outline the kind of analysis that one would like to carry out on the basis of the available data, I present below a preliminary discussion of one of the galaxies shown in Fig. 2.

The galaxy associated with IRAS 1027-395 is listed in the *ESO/Uppsala Survey of the ESO (B) Atlas* (Lauberts 1982) as a disturbed SB galaxy situated in a cluster. It has optical dimensions of 66″ × 48″ corresponding to major and minor axes of 29 and 21 kpc at the adopted distance of 89 Mpc. The integrated blue magnitude and the optical colour in a 62 arcsecond aperture are given as B = 13.69 and B-V = 0.56. If we make standard assumptions to correct for reddening on the basis of the observed Hα/Hβ line ratio and if we assume that the hydrogen line to continuum ratio is the same everywhere in the galaxy (a somewhat questionable assumption) we derive an integrated Hα luminosity of 1.1×10^{-15} W m^{-2} for IRAS 1027-395.

Based on the observed IRAS fluxes at 60 and 100 μm we obtain an integrated infrared flux of 2.2×10^{-13} W m^{-2} yielding a total galactic luminosity of 5.4×10^{10} $L_\odot$. Using data tabulated by Panagia (1973) we then find that the derived Hα and total luminosities could be emitted by 2×10^6 B0V stars. Those stars have masses of about 15 $M_\odot$ and main-sequence lifetimes of about 10^7 years so that we finally derive a rate of formation of massive stars of ~3 $M_\odot$ yr^{-1}. Although this result has been derived by assuming that all stars have the same mass it does not drastically change if we take into account that stars probably form with a mass spectrum that falls off steeply towards higher masses.

The derived star formation rate of massive stars may be a severe lower limit to the total rate of star formation. If the mass spectrum of stars born in a starburst has the same slope as observed for stars born in our own galaxy and if it extends down to about 0.1 solar mass the total starformation rate increases to about 30 $M_\odot$ yr^{-1}. In that case a galaxy would use up most of its available interstellar gas during a starburst in a few hundred million years.

We hope that our study of an infrared complete sample of starburst galaxies at ESO will ultimately provide answers to such fundamental questions as:

- What triggers starbursts?
- How much mass is converted into stars during a starburst?
- How long does the starburst phase last?
- Do all galaxies at one time or another experience starbursts?
- Is there any connection between starburst and Seyfert galaxies (fuelling of central engines)?

Distribution and Access of IRAS Data in Europe

The remarks above may have sufficiently illustrated the need and the potential rewards of ground-based observational programmes to follow-up IRAS discoveries. In view of the huge size of the IRAS database and of the diversity of astronomical information that it contains this is a task that has to be taken up by the astronomical community at large. In order to get prepared for this in Europe we will briefly discuss a few relevant aspects of the future distribution and access of IRAS data in Europe.

TABLE 1. PROPERTIES OF IRAS SURVEY ARRAY DETECTORS

Central wavelength (μm)	Wavelength range (μm)	Detector field of view ($arcminute^2$)	Detector dwell time (s)	Sensitivity at SNR = 10 (Jy)
12	8.5 – 15	0.75 × 4.5	0.19	0.7
25	19 – 30	0.75 × 4.6	0.19	0.65
60	48 – 80	1.5 × 4.7	0.39	0.85
100	83 – 120	3.0 × 5.0	0.78	3.0

As presently foreseen the IRAS catalogues will be published in late November 1984. There will be two main catalogues and several so-called specialty catalogues. The main catalogues are:

1. The point source catalogue (~300,000 sources)
2. The catalogue of small extended sources (present estimate: ~50,000 sources with sizes less than 8 arcminutes)

These will be available on tape and can be obtained in the US from the National Space Science Data Center and in Europe probably through the Centre de Données Stellaires in Strasbourg.

The paper editions of both catalogues consisting of about 5 volumes (about 3,000 pages) will come out some time in the spring of 1985.

To be able to access, display and analyse the IRAS catalogues we are presently setting up an IRAS data centre in Holland at the Astronomical Institute of the University of Amsterdam. A similar centre will be established at the Rutherford and Appleton Laboratories in Chilton, England.

At the IRAS centre in Amsterdam it will be possible to access the catalogues and to extract sources according to a variety of criteria. We have also acquired tape copies of most major astronomical catalogues for comparison with and further analysis of the IRAS data. We hope to have all software ready by November to be able to get going as soon as the IRAS catalogues become available.

Although set up initially for use by the Dutch astronomical community, European astronomers who would like to analyse IRAS data relevant for their own research programmes are invited to get in touch with the IRAS centre if they would like to make use of the facilities in Amsterdam. We will probably be able to accommodate a maximum of two visitors at any time. Interested colleagues should contact Dr. T. de Jong, Astronomical Institute Anton Pannekoek, University of Amsterdam, Roetersstraat 15, 1018 WB Amsterdam, The Netherlands.

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