SOFI Sees First Light at the NTT

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SOFI, ESO's new 1–2.5 μm infrared imager/spectrometer, was installed at the NTT on La Silla in early December 1997 and saw first light as planned on the 6th. The acronym stands for Son OF ISAAC, the larger and more complex infrared instrument being built by ESO for the VLT (see Moorwood, 1992, *The Messenger*, 70, 10, and Lizon, 1996, *The Messenger*, 86, 11), which is now undergoing final tests in Garching prior to shipment to Paranal. By copying some of its technology and using a large subset of its software, the ISAAC Team has managed to build and test SOFI in less than two years since the start of its detailed design and in parallel with the on-going ISAAC and other work. In addition to significantly enhancing the infrared observing capabilities on La Silla, SOFI has also provided valuable experience within the 'VLT environment' now existing at the upgraded NTT telescope in advance of the more complicated installation of ISAAC at the VLT later this year. In addition to the opportunity for testing some of the purely instrumental aspects, this includes some of the new operational features being introduced to ground-based astronomy at the VLT such as automatic

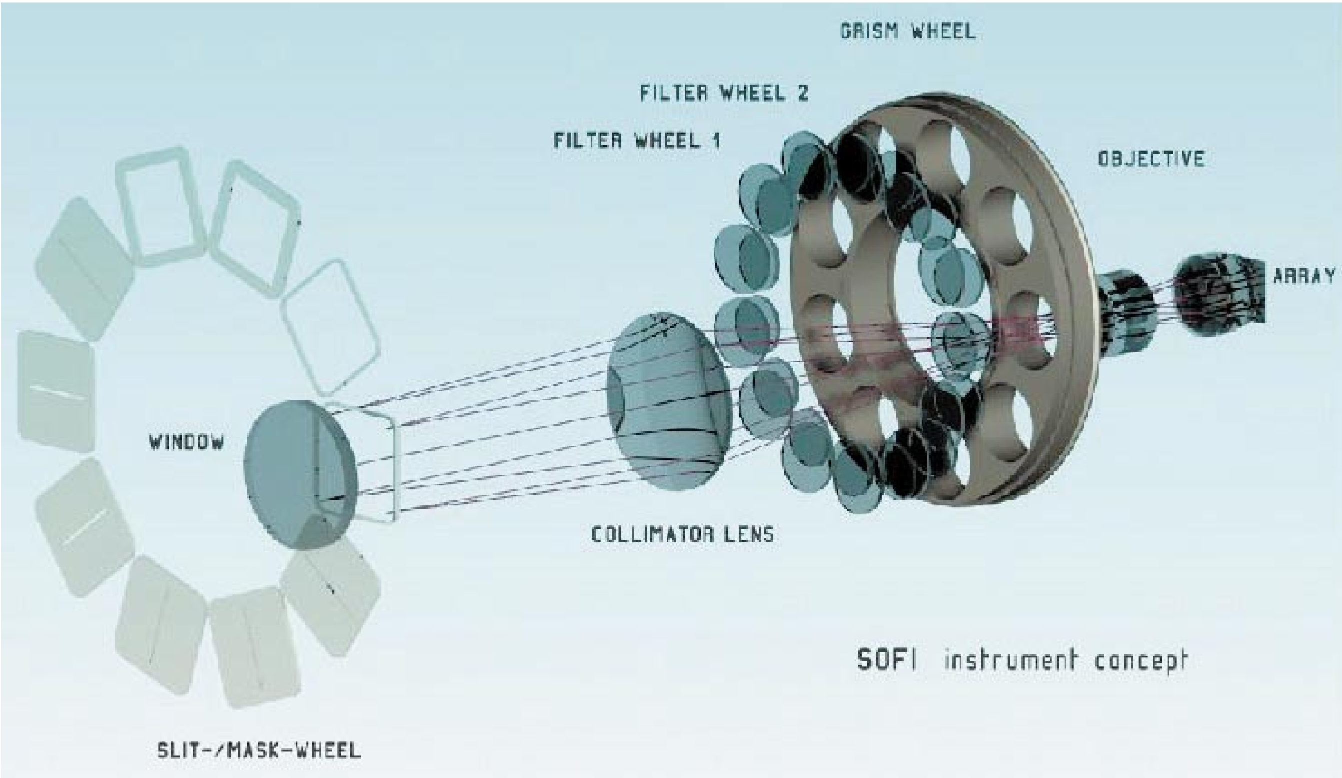

Figure 1: Optical layout of SOFI (see text for description).

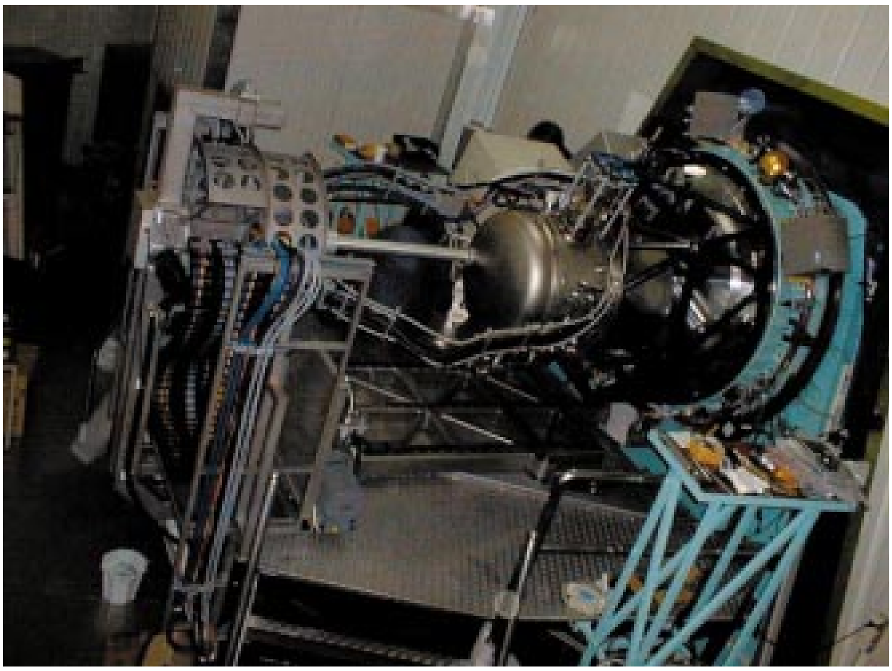

Figure 2: SOFI mounted at the NTT. One of the complications is the need for the co-rotator at the left which carries electrical cables, cooling liquid and gas hoses for the closed-cycle cooler to the instrument and is slaved to rotate with it. (Photograph by J. Brynnel.)

Figure 3: Composite of three 1-min narrow-band-filter exposures of the Orion nebula centred on the 2.166 μm Brγ atomic hydrogen line (blue), the 2.12 μm 1-0 S(1) line of molecular hydrogen (red) and the 1.257 μm [FeII] line (green). Brγ traces hydrogen gas ionised by the well-known Trapezium and other, young, hot stars in the region; the molecular hydrogen emission shows hollow filaments which have been shock heated by matter ejected during the birth of new stars within the OMC1 molecular cloud and the [FeII] emission (only clearly visible here at the end of one of the NW filaments) is emitted by the high velocity fragments impacting the interstellar medium. Pixel scale is 0.29″ and the field is ~ 5′ × 5′ with N at the top and E to the left. Seeing was ~ 0.5″.

execution of observing sequences via pre-prepared Observation Blocks and pipeline reduction and calibration of the data (see D. Silva and P. Quinn, 1997, *The Messenger,* 90, 12).

Why SOFI?

SOFI was conceived within the framework of the NTT Upgrade Plan as a means of providing La Silla with new and greatly enhanced capabilities for near-infrared astronomy which would remain competitive into the VLT era. Science drivers for its design, discussed within the Scientific Priorities for La Silla WG and included in the proposal to the STC, included deep 'wide'-field surveys for high *z* galaxies and low-mass stars plus spectroscopy of galaxy nuclei, supernovae and sources detected by the DENIS infrared sky survey. The first test results reported here show that SOFI, as built, can be a factor ~ 50 faster or reach ~ 2 magnitudes fainter than IRAC2 at the 2.2-m telescope for survey work and can provide low-resolution spectral coverage of the complete 1–2.5 μm region more than 1000 times faster than the, now decommissioned, IRSPEC at the NTT. It also provides superior spatial resolution plus a new polarimetric capability and is still planned

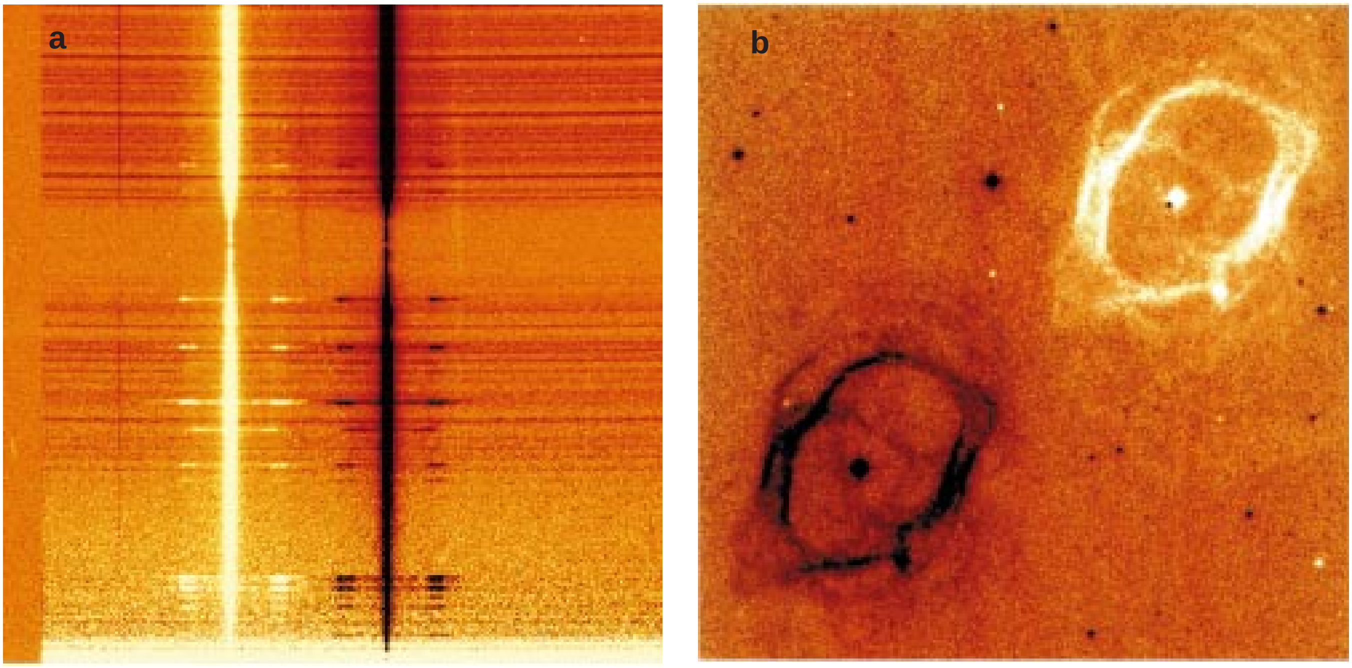

Figure 4a: Red grism 'image' of the planetary nebula NGC 3132. Two 5-min exposures obtained with the object at different positions along the slit have been subtracted to yield 'positive' and 'negative' spectra. Residual sky emission lines (mostly OH) extending across the complete frame are due to their variation between exposures. Several of the lines in the PN spectrum are emitted by molecular hydrogen and are seen to be brightest in a narrow region at some distance from the central star, indicative of a ring-like structure.
Figure 4b: Difference of two 1-min narrow-band 2.12 μm 1-0 S(1) H_2 line exposures with NGC 3132 centred at different parts of the array yielding positive and negative images and showing clearly the molecular ring..

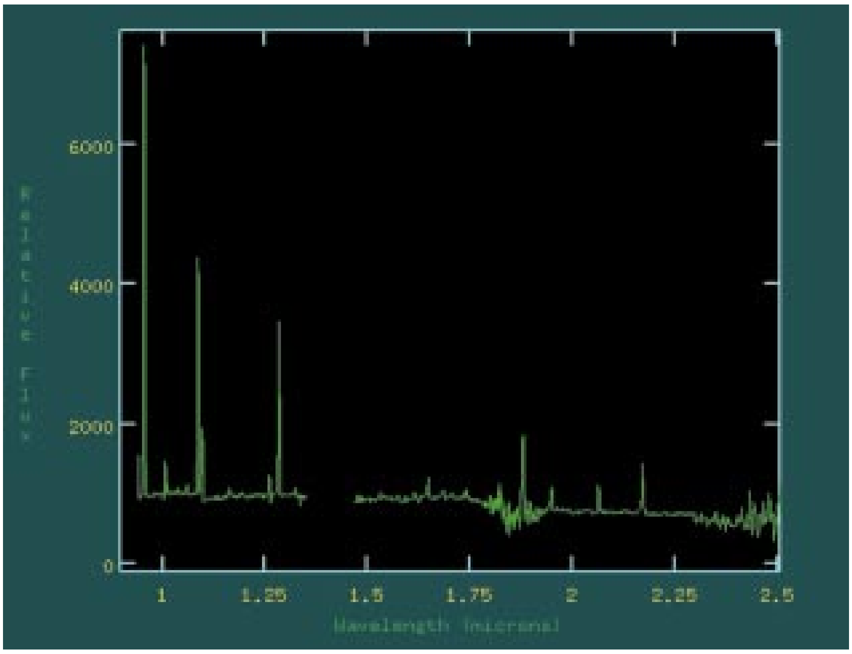

Figure 5: 0.95–2.5 µm spectrum of the dwarf HII galaxy He2–10 obtained using the two grisms. In each case, two 5-min exposures with the galaxy at different positions along the slit have been subtracted. The slit width was 1″, corresponding to 3.4 pixels or 24–34 Å across the spectrum. The region around 1.35 µm suffers from strong atmospheric absorption and has been removed. Atmospheric absorption is also responsible for the increased noise around the Pa (1.875 µm) line. The brightest emission features are the [SIII] 0.953 µm doublet; several H and HeI recombination lines; [FeII] (1.257 and 1.644 µm). CO stellar absorption features are just visible around 2.3 µm.

to be equipped with a medium resolution echelle mode providing that the current problems in developing the required grisms can be overcome. Applications for this new instrument are therefore expected to extend far beyond its primary science objectives. The gains in field and sensitivity, however, are obviously most critical for the deep surveys and open up qualitatively new areas of science which could only be partially addressed with the previous generation of instruments. For many infrared survey programmes, SOFI is also likely to remain competitive with the VLT for some time because its larger field of view compared with ISAAC essentially offsets the smaller telescope diameter. Indeed, many of the programmes already awarded time by the OPC in Period 61 do fully exploit the combination of field and sensitivity e.g. for galaxy and cluster surveys, the use of clusters as gravitational telescopes to detect more distant galaxies and narrow-band searches for [OII] and Hα line emitting galaxies to determine the star-formation density at $z \sim 2$. Follow-up observations e.g. to determine redshifts require complementary optical images or spectroscopy which, for the important $z \sim$ 1–3 range (where the usual optical features are shifted into the infrared), means either with SOFI itself or ISAAC at the VLT. Some of the test results shown here, although obtained with relatively short exposures, have been selected to illustrate SOFI's potential to meet its prime scientific objectives on faint objects while others highlight the additional possibilities offered for detailed studies of brighter, extended, sources.

Instrument Design

Figure 1 shows the layout of SOFI whose optics were designed by B. Delabre and procured and tested with the support of A. van Dijsseldonk. The first wheel carries field masks; various slits for the spectroscopic modes and a special mask for polarimetric observations using the Wollaston prism. Re-imaging of the telescope pupil at the 25 mm diameter Lyot stop is made by the 12 cm diameter, diamond turned, BaF_2 collimator lens which also produces a parallel beam passing through the three wheels carrying broad- and narrow-band filters; grisms; a Wollaston prism and a focal elongator. The final wheel carries three objectives providing a maximum field of 5′ × 5′ and scales of 0.29″/pix, 0.26″/pix (mainly for spectroscopy), and 0.14″/pix (or 0.075″/pix in combination with the focal elongator). The two directly ruled KRS5 grisms currently installed provide coverage of the 0.95–2.5 µm range at R ~ 300–1000 depending on which of the 2, 1 or 0.6″ wide slits is used. A cross-dispersed mode yielding R ~ 3500 is

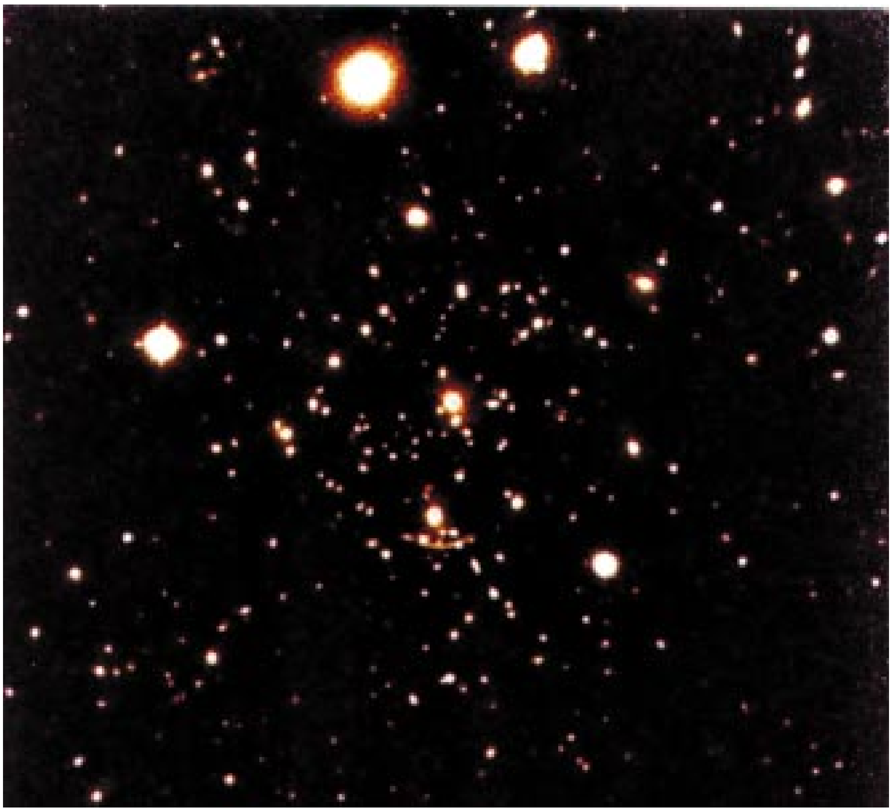

Figure 6: J(1.25 µm) band image of the z = 0.375 galaxy cluster A370, obtained in 'jitter' mode and showing the famous gravitational arc just below the centre. The observations consisted of 24 exposures of 2 minutes each made on randomly-generated telescope positions constrained within a region of 30″ × 30″. The individual exposures have been sky subtracted using a running average determined from the same data and then re-centred and combined. Pixel scale is 0.29″ and the field is ~ 5′ × 5′ with N at the top and E to the left. The seeing was rather poor (~ 1.2″). A J = 22 mag. point source yields s/n = 5 within a 2.5″ diameter aperture.

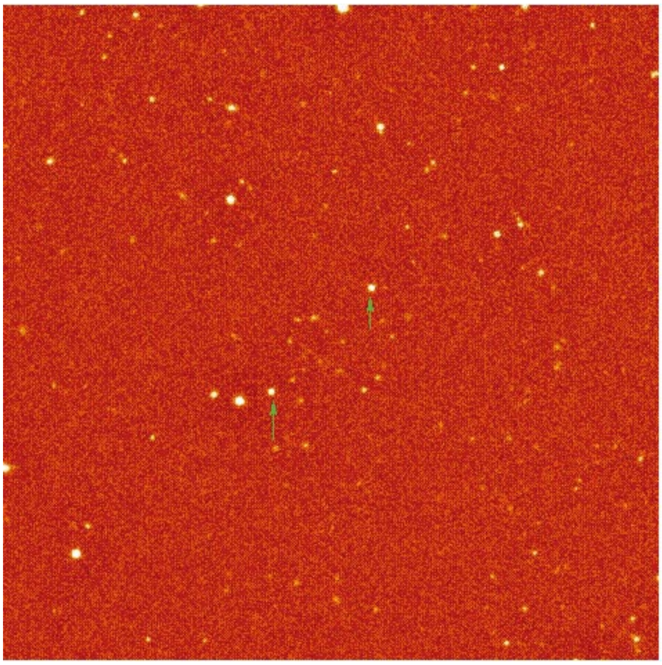

Figure 7a: A 90-min Ks (2.16 µm) 'jittered' image of the field containing the z ~ 2.1 quasar pair 0307–195A,B (marked by the arrows) plus a possible galaxy cluster of unknown redshift located between them. Pixel scale is 0.29″ and the field is ~ 5′×5′ with N at the top and E to the left. Image FWHM is about 1″ and a Ks = 21 mag. point source yields s/n = 4 within a 2″ diameter aperture. Point source FWHM ~ 0.6″ were obtained in a J image of the same field obtained under superior seeing conditions.

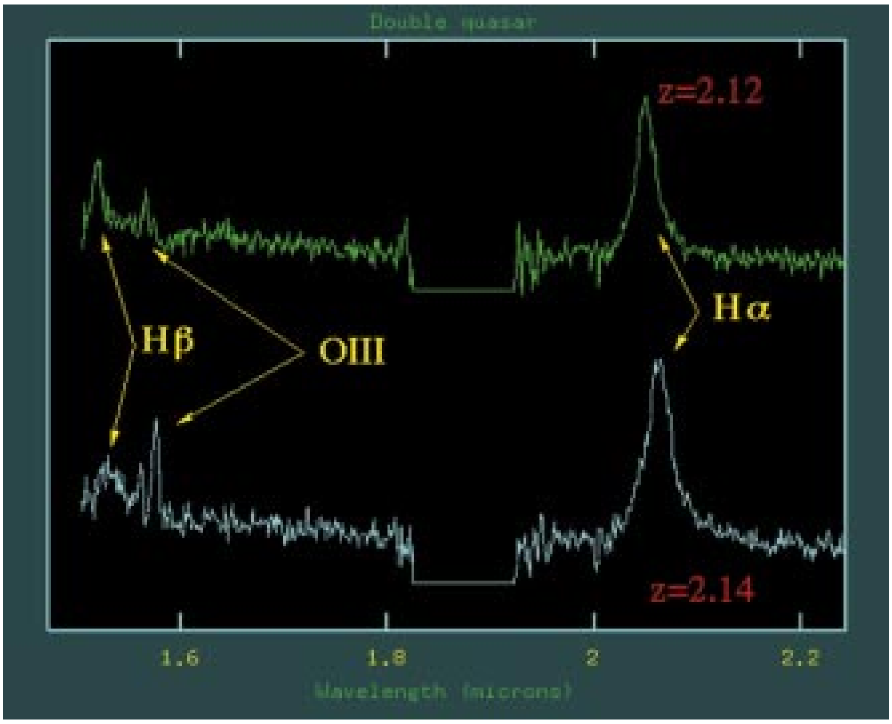

Figure 7b: Spectra of the two quasars in 7a obtained with the red grism. A short imaging exposure was first made to align and centre the objects in the 2″ slit (~ 70 Å). The spectra were then obtained by 'nodding' between two positions along the slit (for sky subtraction) for a total of 80 minutes.

also foreseen in the design but has been delayed due to problems, encountered by the manufacturer, in bonding etched Si wafer gratings to Si prisms to produce the special echelle grisms required. Although the approach is similar to that used successfully for the 10 µm TIMMI grisms (H.-U. Käufl, 1994, *The Messenger*, 78, 4) optical contacting rather than bonding was sufficient in that case due to the longer wavelength.

At the heart of SOFI is a Rockwell 1024 × 1024 pixel Hg:Cd:Te infrared array detector which exhibits fewer than 900 (< 0.1%) bad pixels, extremely low dark current and a read noise of only a few electrons as measured both in the laboratory and on the telescope by G. Finger using the ESO IRACE acquisition system (see Meyer et al., 1997, *The Messenger*, 86, 14).

The optics and detector of SOFI are enclosed within a vacuum vessel and maintained at temperatures of around 77 K by a closed-cycle cooler, assisted by a liquid-nitrogen circuit during the initial cool-down phase. The surrounding cryo-mechanical system, drives, vacuum vessel and external maintenance equipment were largely designed by G. Huster who adopted or adapted ISAAC solutions where possible. Whereas major parts such as the vacuum vessel and maintenance platform were sub-contracted to industry, R. Büttinghaus produced most of the cryogenic functions at ESO using machines controlled by the CAD system used for the design. All the moving functions are driven by gear systems and 5-phase stepper motors as used in ISAAC and adapted at ESO for cryogenic operation by J.-L. Lizon who was also responsible for the overall cryogenic system and integration of the complete instrument with the assistance of A. Silber.

The electronics required to monitor and control the moving functions; vacuum and cryogenic systems; co-rotator system and safety systems is a derivative of the VLT standard ISAAC system and was developed and built by J. Brynnel with the help of E. Pomaroli. Amongst its advanced features are automatic cool-down and warm-up sequences; local fault diagnosis and logging of temperature and pressure data which can be monitored in Garching.

The control software is a large subset of that written for ISAAC under the supervision of P. Biereichel. It includes the Instrument Control (ICS) and Observing (OS) Software developed by T. Herlin and the Detector Control Software (DCS) of J. Knudstrup who also helped J.-G. Cuby to develop the instrument templates used to execute observation and test sequences. The detector acquisition and pre-processing software was developed by J. Stegmeier.

Installation and Test at the NTT

The re-integration and installation of SOFI on the NTT was completed within the 1 week planned with the result that first light was achieved at the beginning of the first test night on December 6th. Figure 2 shows SOFI installed at the Nasmyth focus previously occupied by IRSPEC and SUSI (which is being replaced by SUSI2). Overall, the telescope tests also went extremely well with little night-time lost due to hardware or software problems. Basic tests performed included optical alignment; calibration of the focus pyramid; measurements of scale and distortion; ZP's; backgrounds; flat fielding, etc. Images and spectra were also obtained to test both the instrument performance and the operation of various software templates developed for automatic execution of the main observational and calibration modes. Two examples are the 'jitter' template, which generates random telescope offsets within a defined range between exposures and one for automatic slit centring of objects identified by mouse click on the Real Time Display (RTD) images.

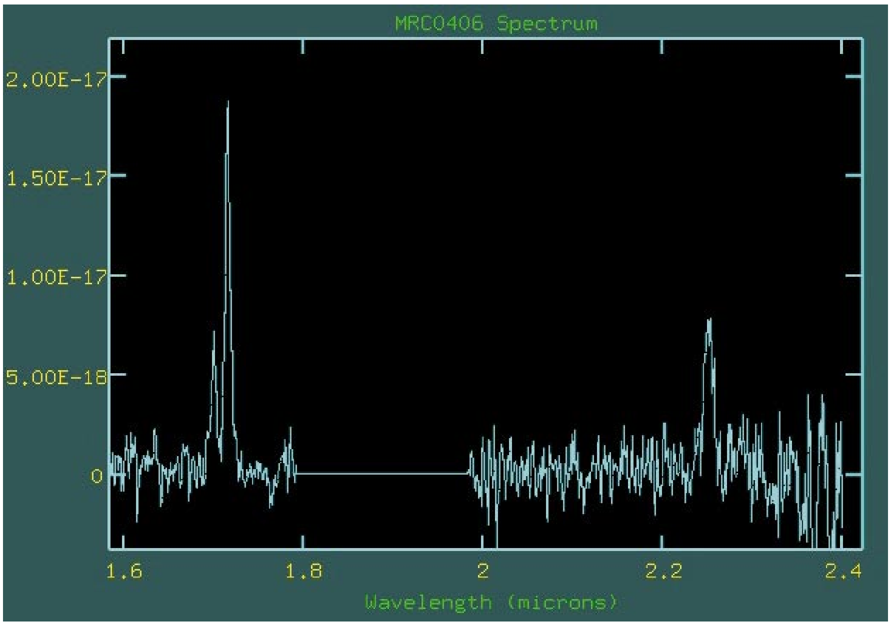

Figure 8: 1.6–2.5 μm 'red' grism spectrum of the z = 2.4 radio galaxy MRC0406-244 showing the redshifted 'visible' [OIII](5000 Å) doublet and Hα emission lines. The 1.8–2.0 micron region suffers from strong atmospheric absorption and has been removed. After identifying the Ks ~ 18 galaxy in a 1-min. imaging exposure and centring it in the 2″ slit (~ 70 Å), spectra were obtained by 'nodding' between two positions along the slit (for sky subtraction) for a total of 60 minutes. A provisional calibration yields fluxes of 7 and 9.10^{-16} erg/s/cm^2 for the [OIII] and Hα lines respectively.

Performance

Figures 3–9 show some of the test images and spectra which illustrate the new capabilities now offered by SOFI. (Some of these plus some not reproduced here can be viewed on the Web at http://www.eso.org/outreach/press-rel/pr-1998/pr-03-98.html). Details are given in the individual figure captions. Overall, the raw images are found to be flat to about 5% before and 1% after flat fielding and the derived point source magnitude limits of J ~ 22.9, H ~ 21.9 and Ks ~ 20.9 (s/n = 5 in 1 hr with 0.75 seeing) are consistent with or somewhat better than those predicted. Under the best seeing conditions experienced, the final images obtained after re-centring and stacking ~ 40 'jittered' exposures have FWHM around 0.6″ (with the 0.29″ pixel scale). Combined with the larger telescope and field plus somewhat higher instrumental efficiency this means that it should be possible to image a 5′ × 5′ field to a given depth up to about 50 times faster with SOFI than with IRAC2 at the 2.2-m telescope. Particularly pleasing is the fact that the Ks (2.16 μm) background is both slightly lower than and appears to be free of the low level, time variable, gradients experienced with IRAC2 at the 2.2-m telescope.

Given the excellent performance achieved overall, it is a pity to have to report the development of some coma in two corners of the large field when using the 0.29 arcsec/pixel LF objective. This has appeared since the first cryogenic tests made with the star simulator in Garching and is most probably due to decentring of one or more of the four, relatively heavy, spring-loaded lenses during temperature cycling. The possibility of replacing it is still being studied. In the meantime, the 0.26 arcsec/pixel 'spectroscopic' objective, used for the 30 Dor image on the front cover, may actually be preferred for some imaging programmes. This and the small field (SF) objective are also largely free of the unexpected appearance, also when using the LF, of extremely faint shadow 'images' of the telescope pupil which could be caused by dust and/or small scratches on the lens surface nearest to the detector (although this cannot be confirmed without opening the instrument). It is doubtful that these would have even been seen on an equatorially mounted telescope. Because of the pupil rotation in an alt-az telescope, however, 'images' of the spider can appear in sky subtracted images although, in practice, they were only seen in the Ks filter and are at or below the shot noise limit in all the 'jittered' images.

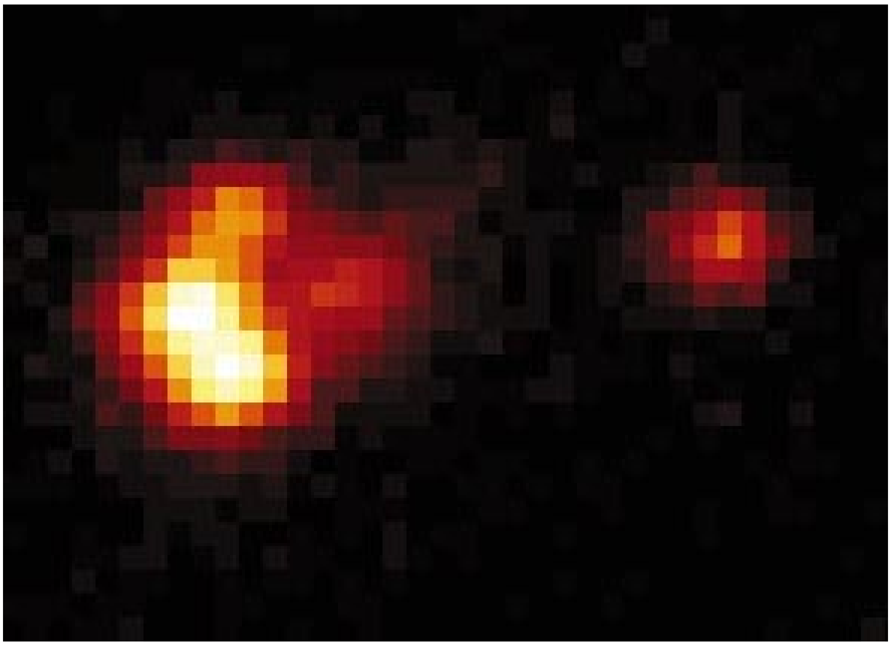

Figure 9: Ks (2.16 μm) 'jittered' (7 × 2 min.) image of the gravitationally lensed quasar RXJ 0911 obtained with the 0.14″/pixel objective. Visible in this small extract of the full image are the lensing galaxy plus three images of the quasar immediately to the left and one to the right.

Future Plans

Despite this early success, SOFI still has to be fully commissioned during runs scheduled for March and May when it is planned to test the DMD supplied P2PP tool (for generating Observation Blocks) and imaging pipeline and to conduct Science Verification observations. These latter will include deep, follow-up infrared images of the 'NTT Deep Field' (see S. D'Odorico, 1997, *The Messenger*, 90, 1) which will be made generally available for scientific use by the community.

Acknowledgements

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