CIRPASS - A Multi-Object/Integral Field Faint Object Spectrograph for the Near Infra-red

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Summary

We propose to complete, commission and operate a new faint object near-infrared spectrograph (CIRPASS - Cambridge IR Panoramic Survey Spectrograph) providing an integral field and multi-object capability over the wavelength range 0.85-1.8μm. Partial support from PPARC (£397.9k) and Gemini (>$100K), matched by substantial investments from the IoA (>£359.5k), will permit rapid completion of this instrument via a straightforward upgrade to an existing spectrograph (COHSI). The aim is to provide the UK community with an early infrared spectroscopic capability at the time of operational handover on Gemini-N. CIRPASS offers a competitive strategy for minimising the effects of the bright OH sky emission and will utilise the latest 2048^2 IR HgCdTe detector available to the IoA through its participation in the Rockwell HAWAII-II development programme. CIRPASS provides an early opportunity for the UK community to exploit a variety of scientific programmes originally planned for the (now seriously-delayed) Gemini Near-Infrared Spectrograph (GNIRS).

Access to the near-infrared spectral region is crucial to explore the $1<z<2.5$ redshift range intermediate between that studied with optical spectrographs on 4-m telescopes and the Lyman-limit regime beyond $z\approx2.5$. During this era, Hubble Space Telescope imaging has demonstrated that galaxies assemble their familiar morphological forms. CIRPASS offers a powerful integral field unit which will exploit the expected high resolution images from Gemini and open a new observational capability for studies of *resolved* galaxies during this important redshift range. As with earlier instrumentation developed for specific programmes (e.g. LDSS-2), a wide range of other programmes can be conducted with this instrument.

The arrangement agreed with Gemini is that for every 4 nights CIRPASS is used by the general Gemini community, the applicants will get an additional night. After commissioning and operational handover, we propose to give these nights to PATT for general UK community use since we are confident that IoA will be in a strong position to write competitive proposals. Given the UK has a 25% share in Gemini, such an arrangement doubles the UK's access to an infrared spectrograph on Gemini at a time when there is likely to be no alternative for faint object studies. It is not unrealistic to expect that CIRPASS would get 50 nights in the first year of which, via this arrangement, 20 would be for UK-led programmes. Without the immediate PPARC funding requested here, the UK will have no spectroscopic capabilities at Gemini handover and no integral field capabilities until the arrival of GMOS (March 2001).

1 Background to this proposal

Our original proposal to construct CIRPASS was submitted to RAP and requested a total of £793K. This design was based on a Rockwell HgCdTe HAWAII 1024^2 array with no upgrade path to a 2048^2 array. Our revised proposal, which follows extensive discussion with the Gemini Project, offers a much more powerful capability and greater access for the wider UK community at lower cost to PPARC. The basic differences are as follows: Firstly, IoA is willing to provide early access to a 2048^2 array through an agreement with Rockwell funded via a private donation. This transforms the capability of the instrument; a 1024^2 array is still available as a backup should delivery of the device be delayed. Secondly, as we now consider it unrealistic to operate COHSI and CIRPASS simultaneously, we propose re-using the COHSI suppressor optics in a conversion to CIRPASS; this saves hardware costs. Finally, in the process of designing a new camera to feed the 2048 array, we have been able to produce an extremely cost effective solution.

COHSI was tested on UKIRT in March and November 1998. Figure 1-1 shows the spectrum of a QSO obtained in a one hour integration and the broad Hβ line is clearly visible. We demonstrated several important technological achievements including excellent sky subtraction, excellent suppression by the hardware suppression optics (particularly the masks - see Ennico 1998) and the very high quality of our IFU (Kenworthy 1998). These achievements are very important for CIRPASS. The throughput of COHSI was initially reported as ~1% in both J and H in March. These low values were partly due to a measurement error and partly due to several key components (gratings, grisms, fibre FRD) each being slightly below specification. From the November UKIRT run the throughput of COHSI is 1.8% in J and 2.4% in H. These throughput values are now very well established and in particular ***the throughput of the COHSI parts we intend to re-use are within specification and will give a total throughput of 17% for CIRPASS*** (see Table 3-2). A further problem with COHSI has been the generally poor performance of the Rockwell PICNIC 256^2 arrays which is exacerbated by the fact that we are operating them in an ultra-low signal regime. CIRPASS will take these improvements forward substantially. By utilising software suppression alongside hardware suppression we eliminate a major component of optical losses, and by utilising the HAWAII detectors, much better performance can be guaranteed. We review the expected performance in Section 3.

The final development relates to the acute shortage of instrumentation available on Gemini during 1999-2001 and, in particular, to the substantial delay to the Gemini Near-Infrared Spectrograph (GNIRS). In November we began detailed discussions with the Gemini Project to consider how we might rapidly build CIRPASS to fill this serious gap in instrument provision for the benefit of the UK community. An addendum to the RAP proposal described the situation as of last December. Since then, a much clearer and more favourable agreement has been reached with the Gemini Project guaranteeing increased access to the UK community in return for the loan of this instrument from late 1999 through September 2001. We demonstrate in this proposal that CIRPASS fulfills many of the key design features consistent with the Gemini Science Requirements Document, in particular offering early use of a powerful integral field unit. Increased access to Gemini for the UK community secured via this proposal will be a highly cost-effective and timely opportunity. The crucial issue, however, is that PPARC has to decide immediately whether to fund the CIRPASS upgrade to take advantage of this window. If CIRPASS is not given the go-ahead now, a major opportunity will be lost.

2 Scientific Case

Extragalactic observational astronomy is currently undergoing a paradigm shift caused by spectacular observations with the refurbished HST, the advent of the immense collecting power of the new generation of 8-10m class telescopes, remarkable improvements in near infrared array detector technology, and the development of adaptive optics systems capable of delivering diffraction-limited image quality (≈0.1") from the ground.

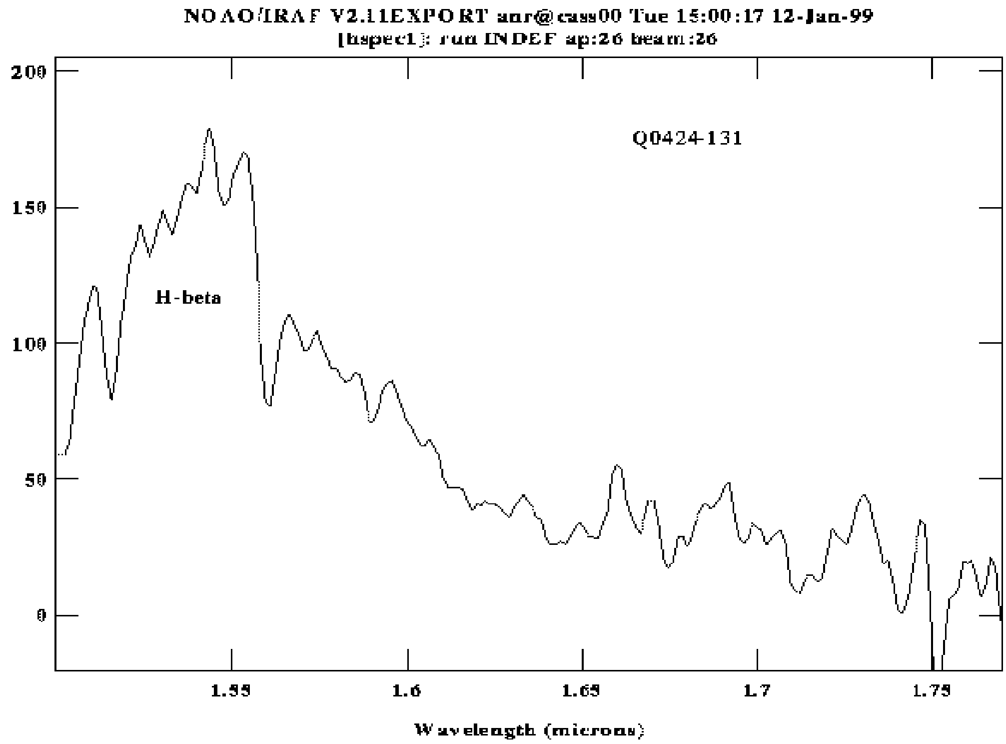


Figure 1. The spectrum of the QSO Q0424-131 (H~16) from a 1 hour exposure. The performance of COHSI would permit us to go considerably fainter. However, on the Nov run only the last night of six was clear and following this observation there was no opportunity to make longer integrations on fainter targets.

However, these improvements over a unprecedented wide range of technological fronts need to be viewed against the sobering backdrop in which we are entering an era when UK astronomers have access by right to only 3% of the worldwide 8m class telescope aperture compared with 15% access to the world's 4m class telescopes.

The UK has a long tradition of developing and exploiting innovative techniques that have kept it at the forefront of observational astrophysics. Undisputed successes are the development of radio interferometry, Boksenberg's IPCS, the suite of AAT wide field fibre optic systems culminating in the AAT's 2DF and, most recently, SCUBA on the JCMT. Each of these instruments revolutionised observational astrophysics. The UK can honour this legacy only by continuing to exploit improvements in technology in a rapid and innovative manner.

Recognising that the Gemini instrument suite might not satisfy all future needs in a number of key and rapidly developing scientific areas, and that a way to obtaining priority and enhanced access to Gemini, and other 8m class telescopes, was to build innovative instruments, the Institute of Astronomy has embarked upon instrumental developments in a number of key technological areas: fibre optic IR spectroscopy exploiting multi-object and integral field capabilities, focal plane masks that deliver coronographic style suppression of night sky emission lines, procurement and operation of large format IR arrays. CIRPASS brings together these elements in a single remarkably powerful and flexible instrument. As a result we now have a timely opportunity to make a significant leap in observational capability when these technological developments are combined with Gemini's collecting area and exquisite image quality .

2.1 Scientific Goals

CIRPASS fufils many of the needs identified by the Gemini project in Jan 1997 (*Future Gemini Instrumention* Gillett et al 1997, GPT-PS-G0075). In the area of *Formation and Evolution of Galaxies*, the provision of R=5000 resolution, multi-object spectroscopic (MOS) and integral field unit (IFUs) modes in the near IR was identified as the highest priority. Such a need was also identified as important for other major scientific applications from searches for brown dwarfs and giant planets to studies of AGN. Many programs also highlighted the need for coronographic capability and resolutions of R=25k. Some of these features were considered so urgent that an option of upgrading GMOS with Hawaii-II (2048^2) arrays was considered. This has proved impractical with GMOS now scheduled for community use on Gemini in mid-2001 a year after the time we propose to deliver CIRPASS to the community. The common-user instrument eventually funded to fulfill these needs (GNIRS) is woefully late (delivery is expected no sooner than late 2001) threatening the UK’s competitiveness with the ESO VLT over a crucial period.

Although CIRPASS has naturally been conceived in order to tackle science programmes of interest to the extragalactic group at the Institute of Astronomy, as detailed in our rolling grant (PPA-G-O-1997-00793), just as in the case of highly successful Low Dispersion Survey Spectrographs(LDSS-I & II) built in Durham, the versatility of CIRPASS will ensure it can be used for a much wided range of astrophysical problems. Specific programs that drive the design and construction include:

- Redshift surveys in the redshift range $1<z<2$
- The star formation history of the Hubble sequence via spatially-resolved spectroscopy of $z>1$ galaxies
- The nature of damped Lyman-α absorption systems.

The combination of the two Keck telescopes and the refurbished Hubble Space Telescope (HST) has completely transformed our view of the high redshift Universe (see Ellis 1997, for a recent review). In only two years, the entire rationale that motivates telescope time proposals in this area has changed. HST is now delivering spatially resolved images of distant galaxies inviting us to consider studies of surface photometry, bulge/disk ratios, internal colour distributions and their interpretation via stellar synthesis modelling (Figure 2-1). Such extraordinarily rich datasets were, hitherto, barely possible beyond the Coma cluster!

The second development is the strongly-held view (Madau et al 1998) that the bulk of the present day stellar density formed remarkably recently corresponding to a redshift $z\approx1.5$. This is consistent with numerous observations including the turnover in the faint blue counts, considerations of redshift-dependent star formation rates and metal production and the predictions of semi-analytical models based on hierarchical theories of structure formation (Baugh et al 1998). These developments highlight the need to target the redshift range $1<z<2.5$ for detailed studies. These developments have profound implications for the way in which we exploit our telescopes.

Redshift surveys in the redshift range 1<z<2

Optical spectrographs are remarkably ineffective in exploiting the redshift range $1.0<z<2.5$ where the bulk of galaxy formation appears to have occurred. This becomes self-evident when it is realised that, despite their large aperture, the Keck telescopes have produced no significant sample of spectroscopically-confirmed galaxies in this range because the strong features (eg [OII] 3727, Hα 6563) are redshifted beyond 1 micron. Secondly, the availability of resolved imaging data drives the development of powerful integral field capabilities for mapping the internal dynamics, star formation rates and line ratios indicative of dust extinction. All of the standard techniques used in the study of resolved galaxies at low redshift become available even at high redshift, subject to surface brightness dimming limitations and spectral resolution constraints. Greatest progress will be made by those equipped to conduct more detailed astrophysical studies of distant galaxies.

There are many unanswered questions which form the scientific basis of this initiative. Firstly, our $z<1$ studies of normal spirals (Abraham et al 1999 and Fig. 2-1) suggest a peak in star formation activity close to a redshift 1 (Brinchmann et al 1998). Beyond this point it is unclear whether large disk galaxies were being rapidly assembled (as predicted by Baugh et al 1998) or whether massive galaxies were in existence at very early times as claimed by Wolfe (1993). Similarly, a non-negligible fraction of $z<1$ field spheroidal galaxies appear to have suffered recent star formation indicative of their continued formation over $1<z<2$ (Abraham et al 1998). Are these results quantitatively in agreement with hierarchical merging? Finally, there remains the extraordinary enigma of the plethora of faint small star-forming dwarfs. What is the fate of these systems and what is their contribution to the global star formation history?

An important aspect, where the gain of CIRPASS over all other instruments is crucial, involves IFU studies of the dynamics and internal characteristics of selected sources in conjunction with their resolved multicolour data (Figure 2-2). Surface brightness is a crucial limitation in the proper exploitation of resolved spectral data and demands the ultimate in scattered light and background suppression. Studies of distant galaxies using optical IFUs on 4-m telescopes have been singularly disappointing (e.g. CFHTs Argus, Soucail et al 1998). Retaining the optimum performance through progress in detectors and design features, as a direct result of our experience with COHSI requires optimised sky-subtraction through the combination of software and hardware suppression.

We have calculated the feasibility of the second phase by combining the Hubble Deep Field (HDF) images of resolved galaxies and the integrated KPNO near-infrared photometry (Dickinson, priv. Comm.) in order to estimate typical surface brightness distributions in the H band. Noting that a continuum s/n=5 is attained in 3 hours on Gemini for a point source of H=22.04-22.5 we find that typical sources estimated photometrically to have $z\approx1$-2 have at least 20-30 resolution elements that would yield useful kinematic data and line ratios. Much depends, inevitably, on the strength of the emission lines. The unique advantage here of CIRPASS is that its spectral resolution will yield internal velocities to a precision of 30-50 km sec^{-1}.

Whilst studies of galaxy formation via the traditional approach of studying the starlight has made spectacular progress, in recent years as a result of work with Keck and HST the study of galaxies selected by their starlight inevitably does not give us the full story. In order to obtain a self consistent and complete picture of the galaxy formation process we must combine studies of the star formation rate with studies of the gas content of the Universe and thus we learn about the underlying metal production and gas consumption rates.

Figure 2-1 - HST images of 3 distant spirals and their deduced prior star formation history from the resolved multicolour analysis of Abraham et al 1999.

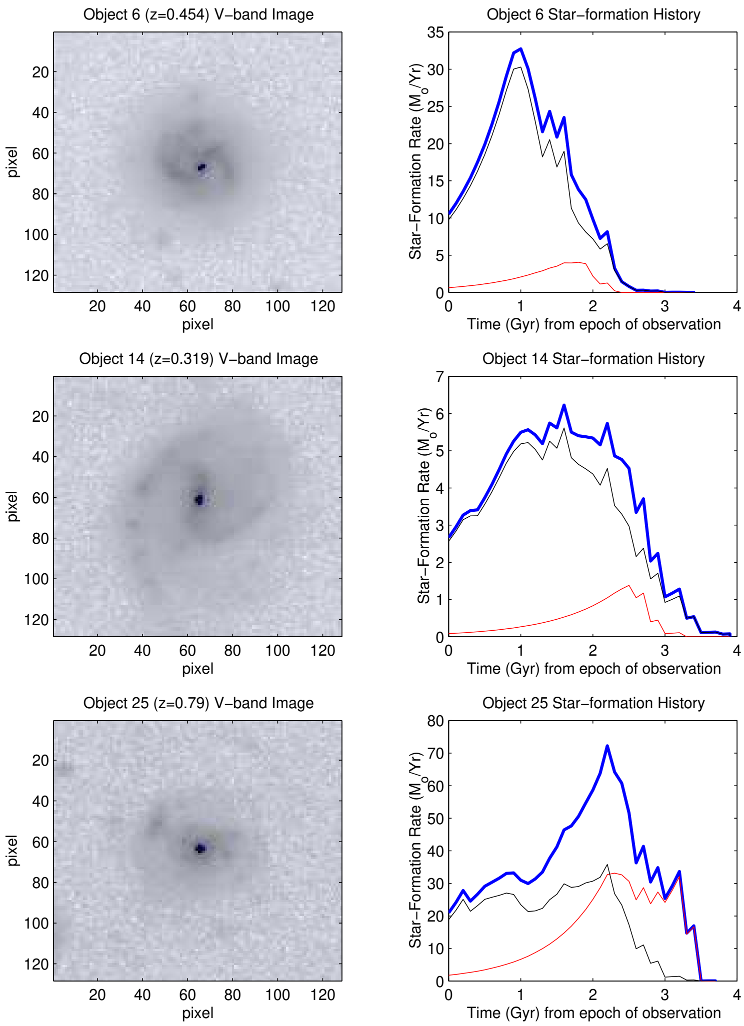
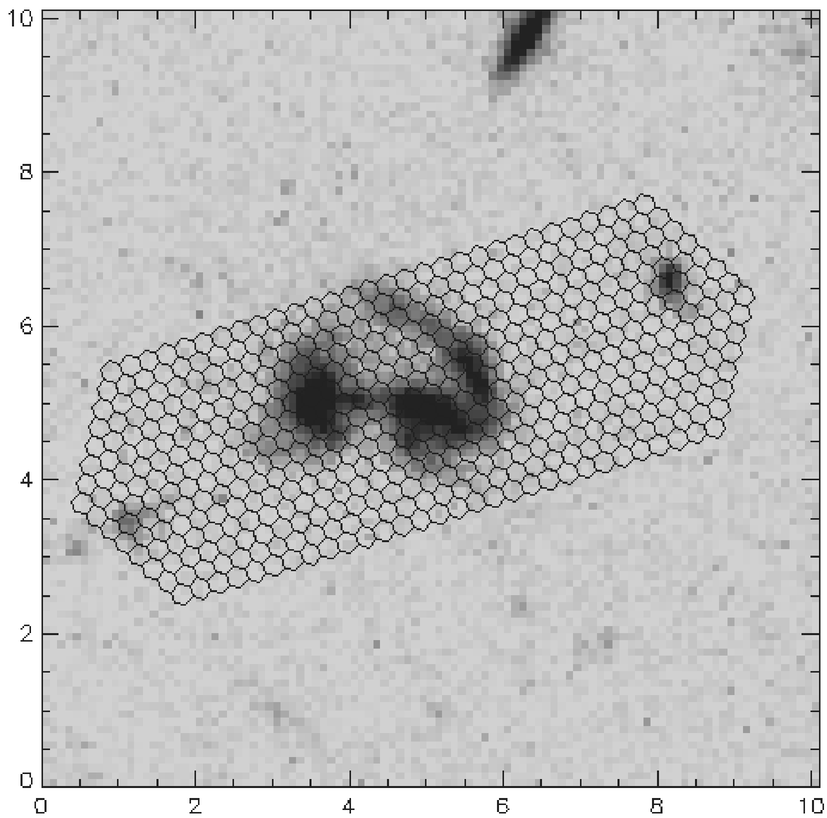


Figure 2-2 - Integral Field Spectroscopy of an HDF galaxy merger using CIRPASS: the spectral resolution is 6-20 times better than COHSI and will facilitate internal dynamical studies.

The example shown here is CFRS 14.1129 in HST F814W. At z=0.831 H-alpha is at 1.202 microns. The fore-optics are arranged to give 0.25 arcsec across each lenslet.



The Nature of Damped Lyman-α Systems

At redshifts above two, the major observable baryonic component is observed via the ubiquitous Damped Lyman-α absorption line(DLA) systems. The study of the star-formation rates, kinematics and metal content of these systems is crucial to our understanding of how galaxies form and evolve. Whereas locally neutral hydrogen is primarily locked up in stars, at high redshift it is contained within these high column density (N(HI)>2×10^{24} m^{-2}) HI absorption line systems, detected via their imprint on the spectra of background quasars. Moreover, the comoving mass density of neutral gas in the redshift range $2.0 < z < 3.5$ is within a factor of 2 of the cosmological density of visible stars in current galaxies (Wolfe et al, 1986; Storrie-Lombardi, McMahon & Irwin(1996)). Moreover, DLA systems provide a sample of galaxies that are selected by gas cross-section rather than integrated starlight and thus give us an independent picture of the galaxian population at high redshift.

The presence of a DLA galaxy implies that the absorber lies very close to the QSO sight-line, as supported by the limited observations available (eg Aragon-Salamanca, Ellis and O'Brien, 1996; Moller & Warren 1998 and refs therein). Attempts to measure the star formation rate in the optical from DLA galaxies with redshifts z>2, using Lyman-α have met with limited success and moreover estimating the star-formation rate from the Lyman-α line is highly uncertain. A more robust method is to use the H-α line. CIRPASS in IFU mode is ideally suited to such a project and moreover allows one to explore the redshift range 1<z<1.7, where it is now believed the major epoch of galaxy assembly occurred. In cases where H-β can be detected we can measure the Balmer decrement and hence determine the reddening. At z~1.5, a galaxy with a star formation rate of 1 solar mass per year will produce an observed flux in H-α of ~1×10^{-17} ergs/cm^2/s so that in 1hr CIRPASS could detect star formation rates of 0.2 solar masses per year with a S/N of 10. However, CIRPASS not only allows the detection of such a galaxy we also get a full 2-dimensional H-α velocity map and hence can determine rotation curves for this important galaxy population.

In summary, CIRPASS will be critical in delivering the first large systematically-chosen population of z>1 galaxies. The faint limiting magnitude of CIRPASS and its high spectral resolution will open up for the first time the prospect of internal dynamical data for high redshift sources. This area is highly competitive world-wide and it will be a great shame if the momentum built up at the IoA in several key technologies (detector development, IFUs, OH masks and spectrograph design) is now lost. It goes without saying that we expect CIRPASS to be used for a wide range of other extragalactic programs ranging from the study of the new SCUBA source population to Gamma-ray burst host galaxies and other problems of new and current interest.

3 Technical Description

3.1 Summary of Instrument Capabilities

The CIRPASS design is versatile as it offers the following options:

- Integral Field Spectroscopy with 500 spatial samples and several image scale options (see Table 3-1)
- Multi-object spectroscopy of up to 180 objects
- Can be used in conjunction with the UH-AO system
- Operation in the range 0.9-1.8μm
- Large wavelength coverage ($\Delta\lambda$=0.44μm) at R~3100 in a single integration with a 2048 array
- Spectral resolutions up to R~26,000
- High throughput as for a conventional faint object spectrograph
- Limiting magnitudes of J=23.3 and H=22.4 in 3 hours (see Table 3-3)
- Focal plane masks to block bright objects in the IFU field of view

3.2 Technical issues raised by RAP

RAP considered a more costly and less well-formulated version of this proposal at its meeting in December 1998. They deferred a decision at that stage, agreed that future funding applications should go to GBFC and raised two technical issues. Firstly, they sought further evidence concerning the performance of COHSI. We have verified the throughput at UKIRT (Section 1, Fig. 1-1) and all our CIRPASS performance estimates are soundly based on the proven behaviour of this instrument. There are no remaining uncertainties in either the expected throughput or sky suppression characteristics of either COHSI or CIRPASS.

More fundamentally, RAP appeared to be concerned that a much higher throughput could be obtained by abandoning the hardware suppression option (i.e. the entire COHSI philosophy) and accepting a higher scattered light component. The trade-off between a pure software suppression device and CIRPASS (which combines both software+hardware) depends on the relative deleterious effects of reduced throughput (CIRPASS) c.f. increased scattered light. We show below (Section 3.3) that even a 1% increase in scattered light in a software suppression device is more damaging than the additional 21% reduction in throughput associated with the suppression optics in CIRPASS. The choice is, therefore, perfectly straightforward.

The suppression optics also allow a very high spectral resolution mode (R>26,000) and are, of course, risk-free and available at no cost.

3.3 CIRPASS - combining hardware and software suppression and improving throughput

An important aspect of the CIRPASS design is the proper elimination of the intensely bright atmospheric OH lines. The continuum flux from typical targets is likely to be fainter than the sky in between these OH lines which are in turn on average 30-50 times brighter. Our design offers the option of hardware suppression to reduce the effects of scattered light and give a substantial gain in signal-to-noise. A further useful byproduct of the hardware suppression optics is the option of using an echelle grating for work at R~26,000. The throughput loss associated with this extra feature is very small (21%).

The total amount of OH flux collected by any instrument is proportion to the telescope aperture, the throughput, the FOV and the wavelength coverage. These are, of course, the parameters that all state-of-the-art NIR spectrographs attempt to maximise and CIRPASS is no exception. The simplistic approach adopted by some 8m spectrographs (e.g. NIRMOS for the VLT) is to let the OH photons through to the detector and then ignore the small fraction of pixels they hit. CIRPASS can readily work in this mode too if the mask is replaced by a mirror. However some fraction of the OH flux will inevitably be scattered by the optics in the spectrograph and be spread over all the detector pixels. The CIRPASS design will minimise the effects of scattering by allowing the option of hardware suppression to remove the OH as soon as possible in the optical train. This is a very important point for J and H band spectroscopy because the sky brightness in between the OH lines is so faint and the detector dark current is so low that the limiting background is due to scattered light. The loss in throughput incurred by allowing this option is very small and the overall gain in signal-to-noise can be considerable. For example, for CIRPASS, if only 1% of the total OH flux entering the spectrograph is scattered uniformly across the detector the limiting magnitude will be brighter by 0.25 magnitudes. On the other hand, in a 3 hour exposure the 5-sigma limit is H=22.08 (see Table 3-3) for a throughput of 0.17 (see Table 3-2). If the throughput is increased by not having the suppression optics the 5-sigma limit is H=22.27, i.e. 0.19 magnitudes fainter so overall a system with higher throughput and 1% scattering is not as sensitive as CIRPASS.

It is important to note that there is no significant disadvantage or risk associated with keeping the hardware suppression/mask option. Only a marginal improvement in throughput is possible in principle by avoiding the extra two passes through the collimator and the mask itself. The 3 mirrors and 4 air-glass surfaces that could be removed have a *measured* total efficiency of 79% in COHSI. In practice these optics cannot be simply removed and we cannot conceive of a design that uses a conventional grating that which would actually be 1/0.79× more efficient. Of course, CIRPASS can be constructed by using the COHSI suppressor optics. The optics exist, are known to work well and they are available at no cost and no delay.

Another crucial difference between CIRPASS and COHSI is the switch from the poor quality 256 PICNIC detectors to the larger HAWAII arrays. The larger format arrays also simplifies the optics. CIRPASS will use either a single Rockwell HAWAII-I array or a HAWAII-II array giving it 8 or 32 times as many pixels as COHSI and enabling the final suppressed spectrum to be recorded at a much higher spectral resolution (R~3000-26,000) than COHSI (R~500). The optical arrangement needed to do this is much simpler than that of COHSI because there is no longer any need to undisperse to feed a separate spectrograph that provides the required low spectral resolution. This simplification gives an increase in sensitivity of more than one magnitude because it removes 2 dispersing elements and an extra fibre feed from the optical path.

3.4 Spectrograph Optical Design

The proposed optical layout of the CIRPASS spectrograph is shown in Figure 3-1 and the main features of its design are summarised in Table 3-1. There will be two fibre feeds: a plug-plate MOS feed and an integral field unit (IFU). The spectrograph itself will sit on the observing floor. The design will use the large COHSI suppressor optics. The first part of the system is a Schmidt in double-pass, the first pass acting as the collimator and the second acting as a camera. The fore-optics will be arranged so that FRD is taken into account, maximising the light collected by the f/5.5 collimator. The simplicity of the collimator arrangement will keep scattering to a minimum in this part of the system allowing the mask to reject a very large fraction of the total OH light coming in from the sky.

For observations at the faintest limits, a reflection grating working in first order provides spectra on the mask at a spectral resolution which is high enough (R~3100 at 1.4μm) to suppress the OH lines. The f/5.5 spectrum at the mask is physically reduced to the size of the HAWAII array by a third pass through the Schmidt (which collimates the beam) and an f/1.35 camera. To select the central wavelength we tilt the whole camera unit to view the appropriate mask area. Tilting the grating would also select central wavelength but would misalign the OH spectrum with the mask.

The current COHSI grating has 400 l/mm and is blazed at 1.2μm. We will purchase 4 additional gratings (see Table 3-1). One will be another 400 l/mm grating blazed at 1.6μm which will give a factor of 1.3× more throughput in H. For MOS work the larger fibres require twice the dispersion to achieve the R~3000 so we will buy an 800 l/mm grating. The other two will be a 900 l/mm grating to give R~11,000 and an echelle to give R~26,000. The near-Littrow design which provides hardware suppression allows these high dispersion options whereas a conventional spectrograph design with a large camera-collimator angle would not.

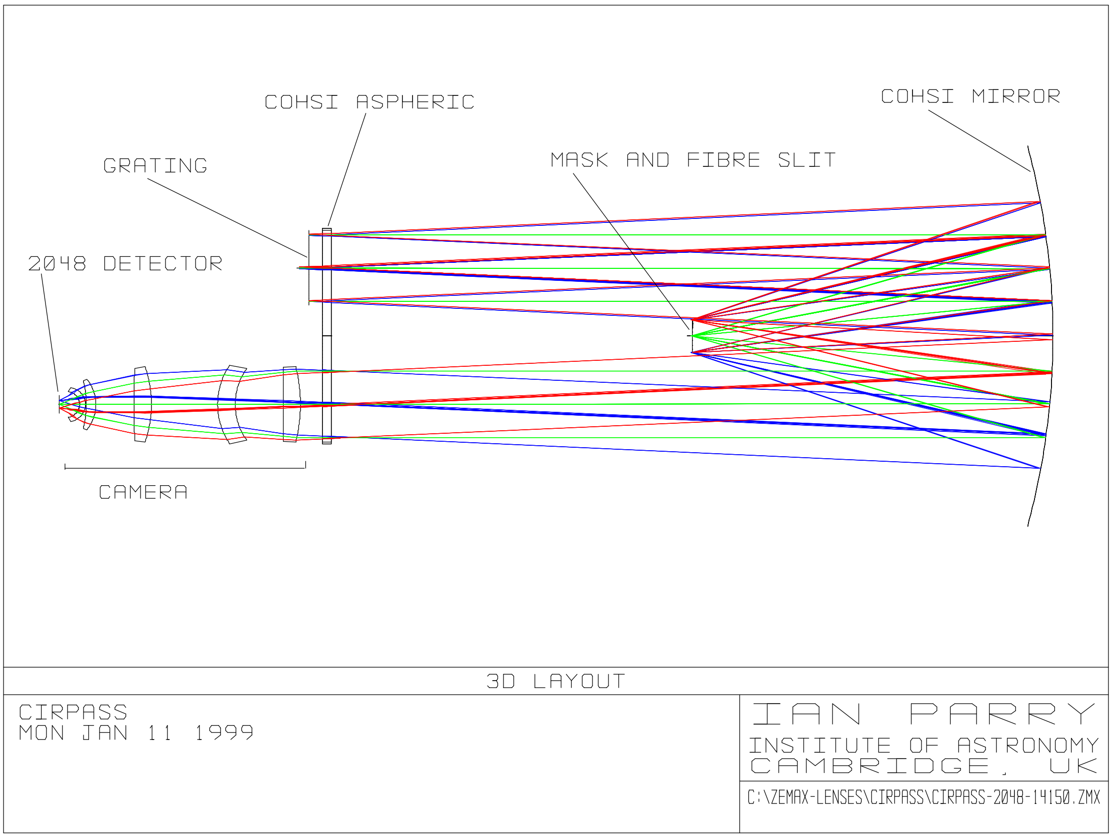


Figure 3-1. Plan view of the CIRPASS optics. The dispersion direction at the detector is out of the page.

Table 3-1 - CIRPASS SPECIFICATIONS

Multi-object mode:	
Number of fibres	180
Fibre diameter	1.0 arcsec
Accessible FOV	6 arcmin diameter
Minimum fibre spacing	13 arcsec
Centre-to-centre spacing of spectra in pixels	5.6
Dispersion at detector with an 800 l/mm grating	1.1 Å/pixel
Spectral resolution R at 1.4µm for 4 pixels	3182
Total wavelength coverage across detector with an 800 l/mm grating	2253 Å
Integral field mode:	
Dispersion at detector with a 400 l/mm grating	2.17 Å/pixel
Spectral resolution R at 1.4µm for 2 pixels	3317
Total wavelength coverage across detector with 400 l/mm grating	4321 Å
Throughput at blaze wavelength (see Table 4-2)	0.17
Number of fibres/lenses	500
Centre-to-centre spacing of spectra in pixels	2
approximate IFU size in lens units	37×14
Number of image scale options	4
FOV for scale option 1: @ 0.36 arcsec/lens	13×5 arcsec
FOV for scale option 2: @ 0.25 arcsec/lens	9.2×3.5 arcsec
FOV for scale option 3: @ 0.12 arcsec/lens	4.4×1.7 arcsec
FOV for scale option 4 (for AO): @ 0.05 arcsec/lens	1.8×0.7 arcsec
High Spectral Resolution Options:	
900 l/mm grating, first order @1.55µm, 2 pixel resolution element	R=11,133, (Δλ=735Å)
79 l/mm grating, echelle @1.55µm, 2 pixel resolution element	R=26,494, (Δλ=309Å)

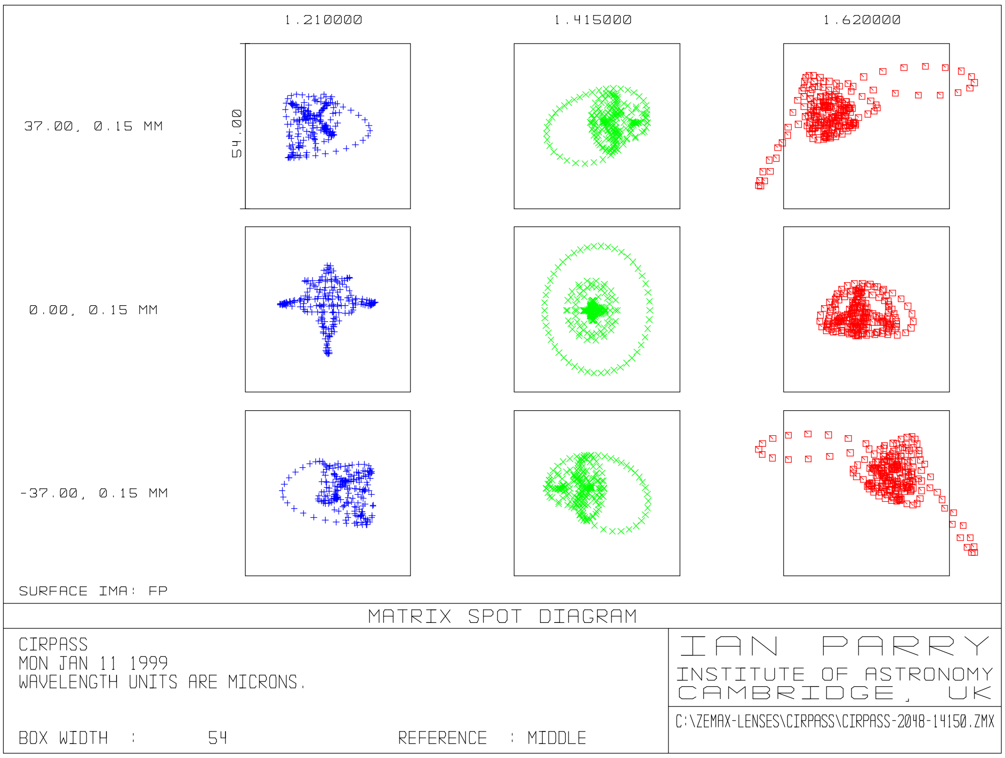


Figure 3-2. Spotplots for CIRPASS. The top and bottom rows are for extreme ends of the slit. The middle row is for the centre of the slit. Wavelength is marked along the top and corresponds to the full length of the 2048×2048 array. The box size is 54µm which is 3 pixels.

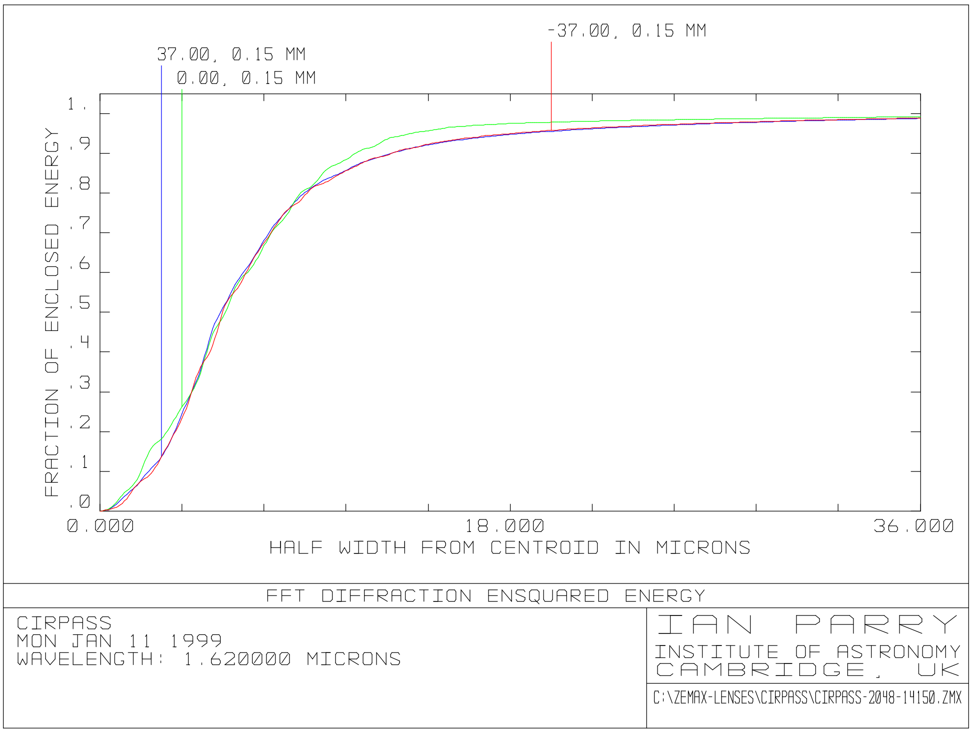


Figure 3-3. Ensquared energy for 1.62µm which is the worst case shown in figure 3-2. Three slit positions are shown - the two slit ends and the centre. One pixel is 18µm. 80% of the energy is in one pixel.

Our previous designs had a fully achromatic camera which allowed the use of cross-dispersion. We now propose to use a new camera design which can feed a 2048 array with excellent image quality thereby doubling the wavelength range covered. The previous design used aspheric surfaces and troublesome materials such as Barium Fluoride and Calcium Fluoride. To make the new camera design cheaper and faster to produce our current design uses only regular Schott glasses and spherical surfaces. The number of elements has also been reduced by allowing some chromatic aberration in the camera we correct by tilting the detector slightly with respect to the optical axis. The camera can use either a 1024 or a 2048 array. The slit length projects to 1024 pixels so the IFU field of view and the multiplex gain are the same whichever array is used . However, the HAWAII-II array gives twice the wavelength coverage.

The chromatic aberrations of the camera rule out cross-dispersed spectra so we have had to abandon this for the MOS mode. Instead of 30 fibres with 6 orders per fibre and full wavelength coverage (as in previous proposals) we will now have 180 fibres with a single order per fibre. For 4 pixel resolution elements we get one quarter of the full (0.85-1.8μm) wavelength coverage in one shot on the 2048 array and to get full spectral coverage it will be necessary to scan through 4 camera tilt positions. This gives more full spectra per night than the previously proposed echelle option because what we lose in wavelength coverage we more than recover in multiplex gain.

We need new masks for both IFU and MOS modes because they use different dispersions. The existing COHSI masks are not suitable because they are not wide enough to accommodate the full CIRPASS slit length. We will also need a blank mask (a plain mirror) for the high dispersion modes which don't require hardware suppression. The costs of these are given in Table 4-3.

To keep down costs and get CIRPASS to the telescope as soon as possible we will work with the fibres and the large Schmidt optics at ambient temperatures. We will block the thermal background using a cold, short-pass blocking filter near the detector. The last 4 elements of the camera will be cooled and housed in a custom dewar with several cold baffles along the optical path. The first camera lens will act as the dewar window. The detector and the blocking filter will be cooled to ~70K by pumping on the LN2 dewar. The optical design is complete and we have a working design with excellent images at the detector. Figure 3-2 shows spot plots for the full system using the 2048 array with a central wavelength of 1.413μm and Figure 3-3 shows that for the worst images 80% of the light is within one pixel.

3.5 Fibre feeds

We already have an IFU with 100 fibres for COHSI. This works extremely well and we believe it is the best fibre-based IFU which uses a lens-array that has been built to date. It could be used to feed CIRPASS and would allow observations at very faint limits to be carried out for point sources (see section 4.8). It is however too small to study the internal dynamics of star-forming galaxies at z~1 which have to be sampled at high spatial resolution and require adequate sampling of blank sky for sky-subtraction purposes. We therefore propose to build a new version with 500 elements. The format we propose to use is shown in Figure 3-2.

We also propose to build a fibre feed for multi-object spectroscopy. This will have 180 fibres of 1.0 arcsec diameter. A lens on the end of each fibre converts the telescope f-ratio to that required by the spectrograph collimator taking in to account the measured focal ratio degradation (FRD) of the fibres. The FOV on Gemini will be 6 arcmin in diameter and it will be possible to place the fibres as close together as 13 arcsec. This will allow the first extensive survey to be carried out of star-formation rates in the redshift range 0.37<z<1.74.

3.6 The prototype CIRPASS System

We have already built a prototype version of CIRPASS which was put together in a very small time for the November UKIRT run. The very short time we took to implement this mode gives us much confidence that we can implement CIRPASS itself in the rapid timescale we propose in section 5. For the prototype we used a low grade 1024 HAWAII detector array poorly suited for faint object spectroscopy because of its high intrinsic dark current. For a camera we used a large format photographic lens augmented by extra elements in the test dewar. This camera suffered vignetting and operated at ~f/3 so it could only view a small area of the mask surface compared to the f/1.35 camera we are proposing here. This gave us a format of 63 fibres in the IFU with a wavelength coverage of 1.5-1.6μm (see Figure 3-4). CIRSI filters were used to block out the thermal glow of the suppressor at long wavelengths.

Although we did not use this with UKIRT due to the bad weather we were able to observe the Mauna Kea night sky without the telescope just before our run began. Figure 3-5 shows the data we obtained. The top panel shows the OH spectrum with the grating deliberately misaligned so that the OH lines are not blocked by the mask. The middle panel shows the mask illuminated with white light to show the blocking features on the mask. The bottom panel shows the night sky spectrum when it is aligned with the mask. In this case we see that some sky lines (due to Oxygen) are not being blocked because we have not included a blocking line on our mask. Also we can see that some of our OH mask features do not appear to be blocking anything because the OH line is intrinsically weak. Despite the crude arrangement, the data obtained is already far cleaner than the low resolution data we get with the PICNIC detectors in COHSI.

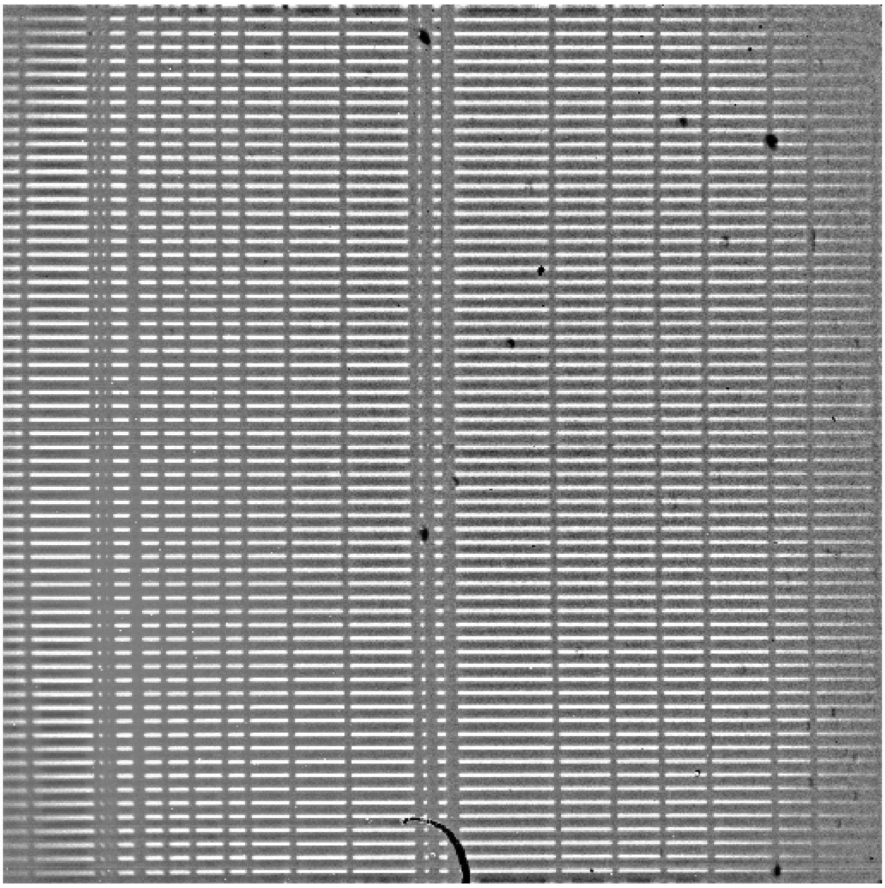


Figure 3-4. The data format with the CIRPASS prototype. The 63 horizontal white stripes are fibre spectra obtained using a continuum source. Note the uniformity of the IFU. The vertical stripes are due to the blocking lines on the mask.

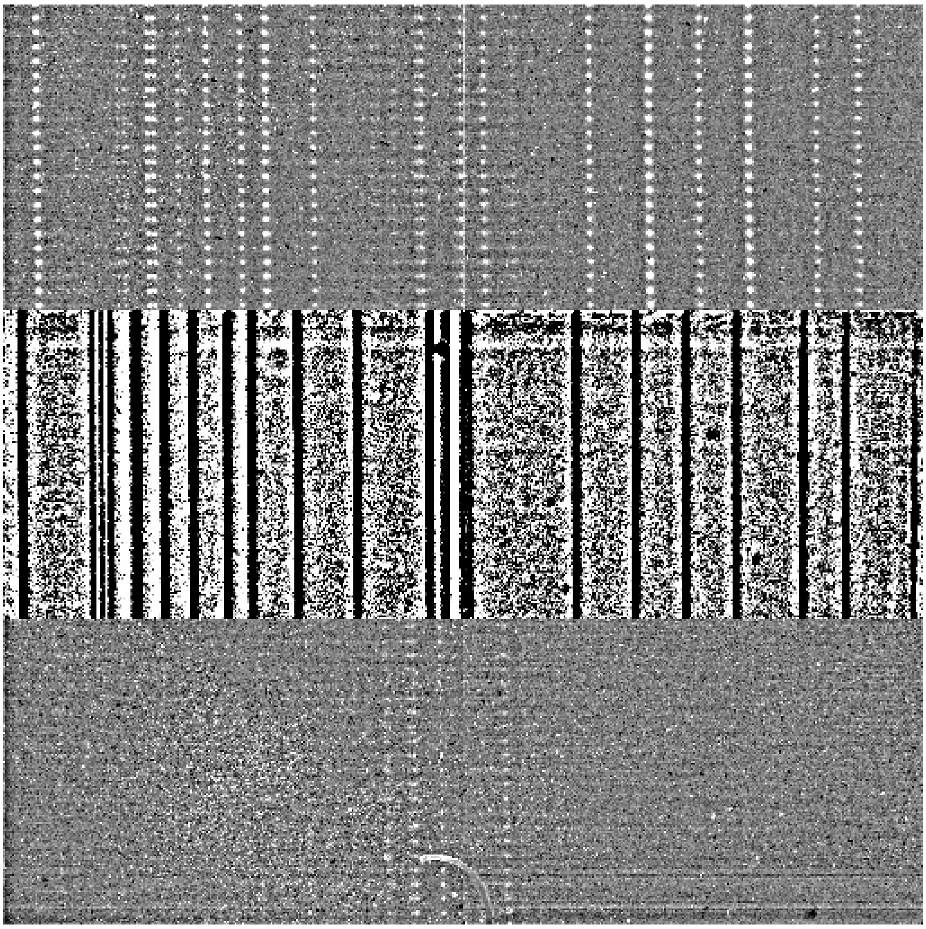


Figure 3-5. A mosaic of 3 exposures using the CIRPASS prototype. The top third shows the spectra of the Mauna Kea night sky with the grating offset so that the OH lines are not blocked at the mask. The middle third shows the mask illuminated directly (not through the fibres). The AR coated mask features are clearly seen. The bottom third shows the suppressed night sky. Some weak oxygen lines which have no mask features can still be seen.

3.7 The telescope focal plane unit

The large physical size of the IFU means that fore-optics are necessary to re-image and magnify the focal plane of the telescope. This is accomplished with two lenses. By changing the smaller of these lenses we can change the image scale at the IFU and therefore offer several scales (see Table 3-1). Changing this lens also allows the instrument to be easily moved from one telescope to another (e.g. UKIRT and GEMINI). Optics for setting up and checking the pupil alignment occasionally have to be introduced. It will also sometimes be necessary to introduce focal plane masks and band pass filters to remove unwanted light.

For the MOS mode a plate holder for the plug plates is required and a TV camera for the acquisition fibres has to be provided. For both modes spectral lamps and continuum calibration sources have to be provided. We will build a versatile telescope focal plane unit that provides all these features with some key mechanisms being controlled remotely. This module will be very small in comparison to a typical 8-m telescope instrument.

3.8 The Detector Hardware and Software Systems

An important development is the IoA's participation in the Rockwell development programme for the new 2048 HAWAII-II arrays. This has become possible following a further significant private donation and we expect to gain delivery of the first device later this year.

The new 2048 HAWAII-II arrays have an architecture that is very similar to that of the 1024 HAWAII-I devices which are used in CIRSI and in UFTI. Some of the final electrical details of the new device have yet to be confirmed. Nevertheless, we are confident that the existing hardware and software systems that we have used for CIRSI and UFTI will work very well with the following modifications:

- New interface electronics between the controller and the array will have to be developed.
- A new array PCB will have to be built.
- The wiring of the camera dewar will have to be developed to give ultra-low noise performance.
- The control software will have to be upgraded.

The funding requested (see Section 4) includes the purchase of an additional controller and the design and manufacture of the necessary interface units for the system. It also includes the cost of a powerful computer which is necessary to operate the detector and other spectrograph systems. The new controller is needed as a spare for the one we already have and is essential if we are to run this instrument for many nights on Gemini in support of the community. The donation covers only the subscription to the HAWAII-II development programme ($250k) which is why we are requesting the costs of the rest of the hardware needed to operate it. The sum requested takes into account the need to make the system very robust and reliable and the need for spares.

3.9 Data Reduction Software

There is no existing data reduction package specifically for reducing fibre IFU data. We have developed IRAF tools for use with COHSI and SPIRAL but there still remains a great deal to be done. Providing a fully functional robust data reduction package is particularly important if we are to offer a substantial amount of community access to CIRPASS. Producing, maintaining and supporting this suite of programs will be one of the main tasks for the PDRA we are requesting.

3.10 Performance

Table 3-2 shows the detailed throughput values for the sub-systems of CIRPASS. We have used 0.97 for each mirror surface, 0.967 for each single-layer anti-reflection (SLAR) coated surface and 0.98 for every multi-layer anti-reflection (MLAR) coated surface. These numbers are lower than manufacturers specifications. *All the values in the table (including the grating and the IFU) are based on the actual measured throughput of COHSI at UKIRT.* The throughput of the CIRPASS optics (from the telescope focal plane to the detector) is 26% and we are confident that when built CIRPASS will meet this specification. The QE of the latest 1024 arrays being delivered by Rockwell is 80% and we have used this in Table 3-2.

Table 3-3 show the limiting magnitude and limiting flux for a single fibre in the IFU for the various sampling scales we will offer on Gemini. Flux limits are given in ergs/cm^2/sec. The limits are for a S/N ratio of 5 and refer to a 2 pixel spectral resolution element. The following assumptions were made in predicting these performance limits. The detector dark current is 0.05 e/sec/pixel. The array is reset every 30 minutes and the readnoise in a 30 minute exposure is 5 e rms. The throughput is 0.17 for both J and H as given in table 3-2 (from outside the earth's atmosphere to recorded photons).

Table 3-2 - CIRPASS Throughput

Item	Efficiency
Atmosphere	0.95
Telescope (3 silver mirrors and central obstruction)	0.88
Fore-optics (4 MLAR coated surfaces)	0.92
IFU	0.70
Spectrograph collimator (1 mirror, SLAR coated surfaces)	0.91
Grating (on blaze)	0.80
Spectrograph hardware suppression pass (see section 4-1)	0.79
Camera (10 MLAR coated surfaces + filter)	0.70
Detector QE	0.80
Total	0.17

Table 3-3 - 5σ sensitivity limits for an exposure time of 3 hours

Spatial sampling (arcsec)	J flux limit (ergs/cm^2/s)	H flux limit (ergs/cm^2/s)	J_{lim}	H_{lim}
0.36	8.9×10^{-19}	6.9×10^{-19}	23.0	22.1
0.25	7.7×10^{-19}	6.0×10^{-19}	23.2	22.2
0.12	6.7×10^{-19}	5.3×10^{-19}	23.3	22.4

4 Project Requirements.

The cost of constructing CIRPASS from scratch would be £819.8k. In practice, of course, by building on an existing device (COHSI) and contributing IoA's privately supplied 2048^2 detector, the request to GBFC is substantially less (£397.9k). The notional sharing of the cost is given in Table 4-1 and the individual contributions are detailed in Tables 4-2 → 4-6.

Table 4-1: Total cost of the CIRPASS project (£K)

Item	details in table	PPARC funds requested	IoA contribution	Gemini contribution	Totals
Existing IoA staff	4-5		45.3		45.3
Additional IoA staff	4-2	137.0			137.0
Gemini Staff				31.2 ($50k)	31.2
Existing Equipment	4-6		314.2		314.2
Additional Equipment	4-3	229.9			229.9
Interfacing/operations equipment				31.2 ($50k)	31.2
Travel/Freight	4-4	31.0			31.0
Totals		397.9	359.5	62.4	819.8

We are requesting this total of £397.9k from PPARC in the form of a grant which runs from Oct 1st 1999 to Sept 30th 2001.Tables 4-2, 4-3 and 4-4 list the staff, equipment, travel and freight we are requesting from PPARC to complete CIRPASS.

4.1 Staff requirements

The new PDRA will start in Oct 1999 for 2 years and work 100% on CIRPASS. To support this instrument at Gemini for a large number of nights is clearly a major undertaking and the PDRA will carry most of the responsibility for doing this with some assistance from other IoA and Gemini staff. The PDRA requested will be the only scientific person working 100% on CIRPASS. Initially, the work will be centred on the commissioning and involve carrying out the commissioning observations, reducing the data, reporting the results and fixing problems. Writing manuals and web pages to assist the community with planning and carrying out their observations will be another important duty he/she will perform.

The new PDRA will also assist with supporting the instrument and community users at the telescope during full operations. A key aspect of the success of CIRPASS is the data reduction software package (see section 3-9). The new PDRA will be responsible for producing and documenting this. He/she will also assist users with data reduction enquiries when they have data. To get a person of high calibre to fill this post the PDRA will be expected to use CIRPASS for his/her own personal observational programs at a level of 25%.

The new design engineer will be appointed from March 1st 1999 on a 1 year contract (we already have a suitable candidate in mind). He/she will produce the manufacturing drawings for the new IFU, the camera dewar, the modifications to the fibre-slit and mask mount, the telescope interface unit and the camera support structure. Because the PPARC funding will not start until Oct 1999 we will cover the salary costs of the design engineer from internal funds and recover them from PPARC later.

Steve Medlen is the IoA's Instrumentation group technician. He has a very broad range of skills and is a qualified electronics technician. He is currently funded up to the end of March 2000 (see Table 4-5). He is a key member of our instrumentation team and we are requesting funds to extend his contract to the end of Sept 2001. His role initially will be an involvement in the development of the detector electronics, testing and enhancing the CIRPASS prototype, construction of the fibre feeds and construction of the camera dewar. Later he will provide the main technical support for CIRPASS at the telescope.

Table 4-2 - Staff funding requested

Staff	period	fraction on project	cost
PDRA (RAIA point 6)	1/10/1999 - 30/9/2001	100%	£45.0k
Design Engineer	1/3/1999 - 28/2/2000	100%	£22.0k
Steve Medlen	1/4/2000 - 30/9/2001	100%	£27.0k
Overheads @ 46%			£43.0k
Total			£137.0k

4.2 Equipment requested

Most of the justification for the equipment costs listed in Table 4-2 is given in the relevant parts of section 3. In addition to these items we are requesting funds for consumables which includes LN2, tools, breakages, software packages, technical documentation, etc. The cost given is based on similar costs for COHSI and CIRSI.

Table 4-3 - Equipment costs requested

Item	refer to section	cost
Camera Optics	3.4	£41.2k
Camera Dewar	3.4	£14.7k
General Mechanical parts	3.4	£10.0k
4 gratings	3.4	£16.3k
Masks	3.4	£8.1k
IFU with 500 fibres	3.5	£37.2k
MOS feed with 180 fibres	3.5	£17.4k
Telescope focal plane unit	3.7	£29.1k
Detector hardware	3.8	£20.0k
Consumables	4	£15.0k
Contingency @10%		£20.9k
Total		£229.9k

4.3 Travel and Freight Requested

To commission, operate and support CIRPASS at Gemini we will need the travel funds detailed in Table 4-4. CIRPASS will make the round trip from Cambridge to Gemini two times. The first one will be for commissioning and the instrument will return to Cambridge where we can further test and prepare the instrument for use by the community. This will be cheaper than moving the CIRPASS team to Hilo to work on CIRPASS there. The second round trip will be for the operational phase. The cost given in the table is based on the cost of shipping COHSI to UKIRT.

We are requesting 12 round trips for a person staying in Hawaii for ~3 weeks. Each trip costs £1.5K. The PDRA would use 4, the PI (Parry) 3, Medlen 2, the project scientist 2 and one member of the science team would use the remaining one. This travel money is essential if we are to maintain a strong enough presence at Gemini to fully support the use of CIRPASS.

Table 4-4 - Travel, subsistence and freight costs requested

Quantity	Item	Cost
2	Shipping equipment: Cambridge → Mauna Kea → Cambridge	£12.0k
12	3 week visit to Mauna Kea	£18.0k
2	3 day visit to ATC	£0.5k
2	visits to Gemini meetings	£0.5k
	Total	£31.0k

4.4 The IoA's contribution

Tables 4-5 and 4-6 list the resources that the IoA will contribute to this project and show what we would have to request from PPARC if we did not already have these resources. These tables do not include senior IoA staff who will work on CIRPASS or the cost of all the development work that has been done at IoA, without which this project would not be possible. Some of this development work was funded by PPARC through the original COHSI grant (£150k).

Table 4-5 shows the IoA technical staff effort being contributed. The IoA's two workshop technicians will manufacture some parts of CIRPASS. The rest will be contracted out and the costs for these items are included in Table 4-3. Our workshop technicians will spend 20% of their time on CIRPASS. Medlen's duties were outlined above.

Table 4-5 - Staff effort contributed by IoA

Staff	Period covered	fraction on project	cost
Steve Medlen	1/2/1999 - 31/3/2000	100%	£21.0k
Workshop effort (2 technicians)	1/2/1999 - 30/6/2000	20%	£10.0k
Overheads @ 46%			£14.3k
Total			£45.3k

The equipment being contributed by the IoA is listed in Table 4-6. The COHSI collimator optics are a major part of the spectrograph (see section 3). The existing COHSI IFU will be used initially for system testing. The 2048 array is a major contribution to this project. If there is a serious delay we will get a top quality 1024 array from Rockwell to use while we are waiting for the 2048 to arrive ensuring that CIRPASS will always be equipped with the best possible detector available. We have a very good working relationship with Rockwell and our total contracts with them include 1 NICMOS-3, 2 PICNICs, 5 HAWAII-Is and the HAWAII-II 2048 array.

For both COHSI and CIRSI we lost a great deal of time because of dewar leaks which were difficult to fix because we did not have a helium leak detector to pinpoint the problem. We tried to hire one but this did not prove to be a good solution due to the high demand for these units and the long waiting list. We will therefore purchase a He leak detector specifically for this project.

Table 4-6 - Hardware contributed by IoA

Item	Cost
COHSI collimator optics	£90.0k
COHSI IFU with 100 fibres	£10.0k
2048 array (or 1024 backup)	£156.0k
Detector control system	£40.0k
Leak detector	£11.5k
Calibrated light source	£2.3k
Single element lab IR detector	£1.9k
Lock-in amplifier	£2.5k
Total	£314.2k

While investigating the COHSI throughput in the lab we used a lock-in amplifier borrowed from the RGO. This was deployed to La Palma when the RGO was closed down. The detector we used also proved unreliable. We will purchase a high quality lock-in amplifier and a detector to do relative throughput measurements of CIRPASS components.

The only calibrated light source we used for COHSI were standards observed through UKIRT. This meant we did not know the throughput before arriving at the telescope and we still do not have an independent measurement of the QE of the Rockwell arrays. We will therefore purchase a calibrated lab light source for this project.

4.5 Gemini's Contribution

The Gemini project will provide US$50k of additional equipment funding and US$50k of Gemini staff effort will be assigned to support CIRPASS at the telescope. The equipment contribution will cover the construction of a telescope interface frame (needed to bring the mass of our telescope focal plane unit up to the 1.5 tonne mass requirement), the modifications to the telescope to ensure that the fibres trail safely to the spectrograph on the floor, some CIRPASS specific handling equipment and incidental operational costs. The staff effort will include software support, design and construction work for the telescope interfacing and general (electrical, mechanical, etc.) support.

5 Organisation, Time-scales and Management

After operational handover (June 30th 2000) CIRPASS will be available for use by anyone in the Gemini partner countries who is awarded time through the allocation committees. For every 4 nights awarded, the IoA, as instrument builders, will receive one of the nights and this will be donated to the UK community and allocated to observers through PATT. In practice PATT and the other partner allocation panels will meet at about the same time and various projects will be allocated time on CIRPASS. The bonus nights will afterwards be allocated to the best UK proposals that were below the cut at the PATT meeting.

Ian Parry will be the PI for this project and will spend on average 50% of his time on it. His duties will be project management, optical and mechanic design, testing, commissioning, supporting the operation of CIRPASS at the telescope and involvement in the scientific exploitation.

Craig Mackay will be responsible mainly for the detector system and will spend on average 1.5 days per week working on CIRPASS. He will also participate in the general management of this project.

Table 5-1 - Project Milestones

Milestone	Date
GBFC approves project	Jan 26/27th 1999
IoA activity starts	Jan 28th 1999
Rockwell 2048 array delivered	end July 1999
Camera optics delivered	mid-July 1999
Camera dewar delivered	end-July 1999
CIRPASS PDRA starts new post	Oct 1st 1999
First community use of CIRPASS	July 1st 2000
End of project	Sept 30th 2001

Richard Ellis, Richard McMahon, Bob Abraham, Alfonso Aragon-Salamanca, Max Pettini, Pierro Madau, Nicole Vogt, Annette Ferguson, Jan Kleyna and Francine Marleau will form the IoA science team for the project with Richard McMahon dedicating 20% of his time as the CIRPASS Project Scientist. This team will ensure that the instrument design is focused on the important scientific goals and liase with community users about the scientific exploitation of CIRPASS. They will also plan the commissioning observations and oversee the production of the data reduction packages.

The instrument will at all times be the property of the IoA. During the period July 1st 2000 to Sept 30th 2001 CIRPASS we reserve the right to use CIRPASS on any other telescope (e.g. UKIRT). This has been agreed with the Gemini project team. They wish to allocate blocks of time to CIRPASS to minimise instrument changes so there will periods when CIRPASS is not mounted on Gemini.

The main project milestones are given in Table 5-1. This is a very rapid timescale but we are confident we can achieve it. Apart from the 2048 detector there are no technological risks and this is totally backed up by the availability of a 1024 array. The other key deliverables which might delay the project are the camera optics and the IFU. For each of these we already have a backup system (see section 3) which will allow us to continue with the commission phase (up to June 2000) and even beyond for a very limited number of science programs. A GANTT chart for the project is attached.

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