ROGUE - the Rapid Off-axis GUider Experiment

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ABSTRACT

Near infrared imaging spectroscopy at spatial resolutions of 0.5 arc seconds will fundamentally change our understanding of active galactic nuclei. This long desired capability has been achieved for the first time by the latest generation of MPE instruments, ROGUE and 3D. ROGUE, the Rapid Off-axis GUider Experiment, is a low order adaptive optics system performing tip-tilt correction in the near infrared using natural guide stars. 3D is the MPE near infrared imaging spectrometer capable of *simultaneous* imaging and spectroscopy of the entire H and K atmospheric windows.

ROGUE is capable of tip-tilt correction at 40 Hz in a 4 arc-minute diameter isokinetic patch using natural guide stars as faint as 18th magnitude. We discuss the design of the instrument, present the first astronomical results, and outline future efforts to incorporate variable image scales.

1. INTRODUCTION

The MPE 3D imaging spectrometer[1] is an unique instrument capable of simultaneous imaging and spectroscopy over a $8'' \times 8''$ field in the H (1.4 to 1.8 μm) and K (1.95 to 2.45 μm) atmospheric windows. With 3D, spatially resolved spectra of extended objects, like active galactic nuclei, are now possible for the first time. A detailed description of 3D is provided by Krabbe et al. elsewhere in this volume[2].

The atmospheric seeing dictates the spatial resolution obtained by 3D. We have built a tip-tilt interface for this imaging spectrometer, in order to enhance its resolution. ROGUE, the Rapid Off-Axis GUider Experiment, would allow us to investigate the nature of double nuclei (e.g. Arp 220) spaced only $1''$ apart. The nuclei of active galaxies and quasars are point-like in appearance at visible wavelengths. As we are interested in studying the nature and environments of these types of objects with 3D, it is essential to be able to track on very faint guide stars, down to 18th or 19th V band magnitude. This was a major goal for the ROGUE effort. Even with this faint magnitude limit, sky coverage will be close to 100% only if we used the entire size of the isokinetic patch. Thus, a large field ($4' \times 4'$) was the second major goal.

We describe below the design of the instrument, and present a sample result from a recent observing run to illustrate the prowess of ROGUE in combination with 3D.

2. MOTIVATION

2.1 The Merits of Tip-Tilt

Adaptive optics offers the promise of providing diffraction limited images at 4 and 8 meter class telescopes, thus allowing ground based instrumentation to compete with observations made from space. However, a tip-tilt system can only compensate for the lowest order terms in the wavefront distortion. As such, one is tempted to doubt the merits of implementing a tip-tilt corrector, given the cost and effort required to construct such an instrument. We would like to emphasize the many advantages a tip-tilt system can provide, especially when linked with the MPE 3D imaging spectrometer.

One can view an adaptive optics system as concentrating energy normally spread over the seeing disk (FWHM $\sim 1''$) into a diffraction limited spot (FWHM $0.11''$ at a 4 meter telescope and 2.2μm wavelength). A tip-tilt system, correcting only the lower order aberrations, typically concentrates about 20% of the energy into the central diffraction limited spot[3]. This results in only a modest decrease in size of the seeing disk. However,

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the gain of tip-tilt correction becomes apparent when one considers that, under typical seeing conditions, only 3% of the energy is contained in the diffraction limited spot. For an imaging spectrometer like 3D, this increase in energy in the diffraction limited spot from 3% to 20% represents a large gain in the signal to noise ratio (SNR) of the spectrum in each pixel.

The gain achieved by a tip-tilt system is a strong function of D/r_0, where D is the telescope diameter, and r_0 is the scale length for atmospheric turbulence at the observed wavelength. Tip-tilt is very effective when D/r_0 is a few, and loses its efficiency rather rapidly when D/r_0 exceeds 10. For operation in the H and K bands, (where r_0 is approximately 0.7 meters) tip-tilt correction is effective at 4 meter or smaller telescopes[3].

2.2 A perfect auto-guider

Another benefit of a tip-tilt adaptive optics system is that it serves as a perfect auto-guider for the telescope. This feature is of particular relevance to an instrument like 3D. Spectroscopic observations in the near-infrared alternate between source and sky frames every 100 seconds, in order to correctly subtract the time-varying OH line emission from the atmosphere. Each source frame has an adjacent sky subtracted from it, and the resulting frames are then co-added to yield the sky-subtracted data set. It is necessary for the source to maintain its position relative to the detector during the course of an observation, as any misalignment between successive source frames lead to a degradation in spatial resolution. Differences in source position, due to telescope tracking errors, can be removed by re-aligning the source frames during data analysis, but this technique is only applicable if the source can be detected in a single 100 second integration. For fainter sources, one has to rely on the accuracy of telescope tracking. With a tip-tilt guider, relative alignment is automatically guaranteed, even when the telescope offsets are large ($\sim 2'$).

Re-aligning successive source frames is also a problem for bright sources if there is no point source in the field of view. As 3D has a small ($8'' \times 8''$) field of view, this is often a problem. A tip-tilt system allows one to choose a field with an arbitrary offset relative to a nearby point source (often the galactic nucleus, for observations of external galaxies).

3D operates with a pixel size of $0.5''$. Reducing the pixel size further would reduce the field of view and decrease the signal to noise ratio in the spectra. Under good seeing conditions with tip-tilt correction, $0.5''$ pixels would significantly under-sample the seeing disk. This problem can be alleviated to a large extent by combining several exposures, each with the source placed at a different position with respect to the pixel boundaries. In other words, by moving the source by a fraction of a spatial pixel between successive exposures, one can better sample the atmospheric seeing disk. With this technique, the resolution of the instrument is no longer dictated by the spatial pixel size, but rather by the intrinsic size of the seeing disk. Such a scheme can be successfully implemented only if the source position can be maintained to a small fraction of the pixel size, an accuracy outside the range of most autoguiders, but certainly within the capabilities of a tip-tilt system.

3. INSTRUMENT DESIGN

3.1 Design Constraints

The design of ROGUE is dictated by few principal constraints. The necessity of tracking on a guide star as faint as $V = 18$ demands high throughput in the visible light (sensing) channel. At the same time, the transmission in the infrared channel cannot be compromised, as it would adversely affect the sensitivity of 3D. This requirement places a constraint on the number of elements in both optical paths. The operating frequency should be faster than the frequency of atmospheric turbulence. Further, since the correction is always applied at the end of the sampling period, one needs to oversample by at least a factor of 3. The time scale of atmospheric turbulence corresponds to a frequency of 12 Hz, for operation in the K band at 4 meter class telescopes. The operating frequency of the tip-tilt system must exceed 35 Hz for effective compensation.

The tip-tilt mirror is preferably placed at an image of the telescope input pupil. If this condition is not met, movements of the tip-tilt mirror effect the background level seen by the instrument. This is particularly important in the thermal part of the K band (region of the K band where blackbody radiation from the warm telescope becomes significant).

Changes in the position of the guide star must be fed back to the sensing channel. Consequently, the tip-tilt mirror must be placed in the ray path of both the visible and the infrared radiation from the telescope. As explained above, we should also place the tip-tilt mirror at an image of the telescope pupil. This constrains the optics which images the telescope pupil on the tip-tilt mirror to operate efficiently over a very broad wavelength range, from 450 nm to 2500 nm. As it is prohibitively expensive to manufacture anti-reflection coatings for such a broad wavelength range, we were forced to adopt reflecting optics for this purpose. The use of reflective optics also requires an off-axis optical setup.

The angle between the science target and the guide star cannot exceed the angle over which atmospheric turbulence is correlated. However, if one is interested in correcting only the tip-tilt term of atmospheric turbulence, one can pick a guide star within the *isokinetic* patch, which is somewhat larger than the isoplanatic patch. At an operating wavelength of 2.2 μm, the isokinetic patch can be as large as $4'$ in diameter, under good seeing conditions. In order to maximize our sky coverage, ROGUE is designed to image a $4'$ field of view in the visible (sensing) channel. The large field of view, combined with the necessity to use off-axis reflective optics, made the optical design rather challenging.

The level of difficulty of an optical design is directly related to the amount of aberration which can be tolerated. In the case of ROGUE, the infrared channel has a very small ($8'' \times 8''$) field of view, posing no serious optical design problems. The aberration specification for the sensing channel is a fraction of an arc second over the entire $4'$ field for the guide star. Symmetric aberrations, such as spherical aberration, yield a spot which is blurred but still possesses circular symmetry. These are not as detrimental as asymmetric aberrations, such as coma. Although only a few arc seconds of the $4'$ field is utilized at any given time, the system's response must be similar for all points in the field of view, to prevent any loss of freedom in choosing the guide star.

3.2 Description of the instrument

A version of ROGUE was built to operate at the Cassegrain focus of the European Southern Observatory 2.2 meter telescope on La Silla, Chile. This telescope is fitted with an infrared secondary, which delivers a f/35 beam at the Cassegrain focus. Currently, we are in the process of constructing a second version of the tip-tilt system for operation at the f/11 focus of the 4.2 meter William Herschel Telescope on La Palma, Spain, and at the f/10 focus of the Max Planck Institut für Astronomie 3.5 meter telescope on Calar Alto, Spain. As the beams from the two 4 meter class telescopes are much faster, the imaging optics within ROGUE has to be substantially modified. We present here the design of the system for the two 4 meter class telescopes, which is similar in principle, but not in detail, to the system commissioned in August 1994 on the 2.2 meter telescope on La Silla.

3.2.1 The Sensing Channel

Figure 1 shows the layout of the visible light channel of ROGUE. The relay system, which consists of two spherical imaging mirrors and a spherical tip-tilt mirror, forms a 0.875:1 scaled version of the telescope focal plane. The entrance pupil of the telescope is imaged onto the tip-tilt mirror. The design is based on the Offner relay system, slightly modified due to the non-unit magnification requirement. The size scale of the intermediate image formed by the relay system is set by the quadrant detector assembly, discussed below in detail.

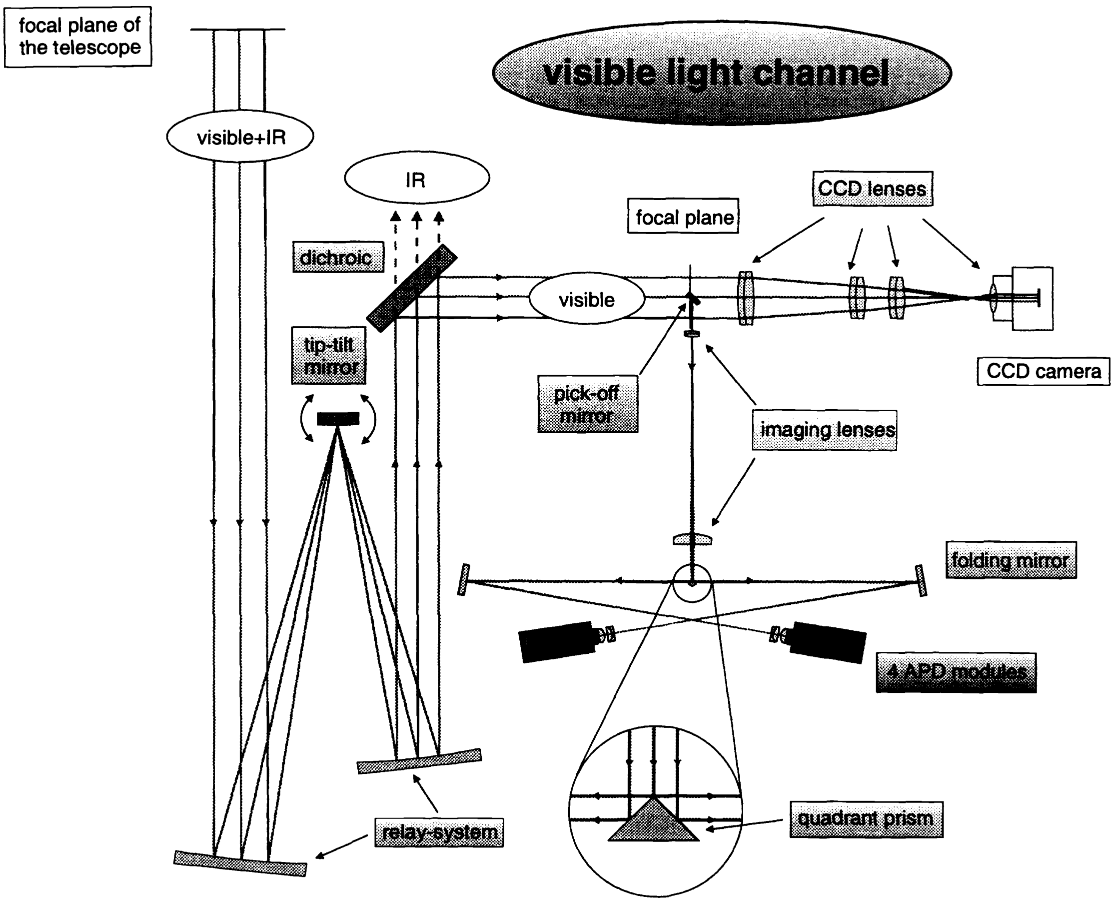

Figure 1: Schematic drawing of the optical layout of the visible light (sensing) channel of ROGUE. The shape of the quadrant prism is shown in the inset.

A dichroic plate is interposed in the beam before the intermediate image plane. The dichroic is designed to reflect light between 450 and 900 nm and transmit light between 1400 and 2500 nm. The reflected light, used for the tip-tilt sensing channel is further split between two systems. The CCD camera channel images the entire 4 arc minute field on the central quarter of a 1024 × 1024 chip. As ROGUE uses all the light (450 nm to 2500 nm) from the telescope, some method of imaging the field of view is required in order to locate the source and the guide star. In principle, one can use the telescope acquisition cameras for this purpose. However, as ROGUE is a travelling instrument, one would have to repeatedly determine the offsets and rotation angles between the acquisition camera co-ordinate system and that of the quadrant detector. The problem is greatly simplified if the imaging capability is intrinsic to the instrument. Aberrations are not important in the CCD channel, as it only serves as an acquisition camera.

3.2.2 The quadrant detector

The quadrant detector assembly is the heart of the instrument. A magnified image of the guide star is projected onto a quadrant prism. Light from each quadrant of the prism is then focused onto the detector of a Single Photon Counting Module (SPCM). Each SPCM consists of a cooled, passively quenched Avalanche Photo Diode (APD) coupled to a preamplifier. A TTL compatible pulse, 200 ns wide, is produced at the output for every detected photon. The detectors operate at a peak efficiency of 60% with a dark rate of 10 counts/s. The response is linear upto $\sim 10^6$ counts/s. The image motion is determined by measuring the relative counts in the four quadrants.

The entire quadrant detector assembly is mounted on a translation table, with a range of 50 mm in two perpendicular directions. A small section of the focal plane is relayed to the quadrant detector system by a pick-off mirror located in the image plane. The pick-off mirror is rigidly attached to the quadrant detector assembly. The pick-off mirror obstructs the view of the CCD camera, so that it is not possible to view the guide star being used for sensing via the CCD. However, it is a simple matter to move the pick-off mirror out of the way in order to image the entire field. It is normally not necessary to image the field while guiding.

The size of the intermediate image is dictated by the travel of standard translation stages. In our design, 45 mm corresponds to $4'$. The scale of the intermediate image in turn fixes the magnification of the relay system. The scale of the guide star image on the quadrant prism is chosen to be as large as possible, so that edge effects do not play a significant role. However, as the active area of the APDs is only 100 μm in size, a large demagnification is required between the quadrant prism and the SPCMs. This determines the size of the quadrant detector assembly.

The dynamic range of the SPCMs and of the CCD camera is much smaller than the desired 20 magnitudes (10^8). Operating at 40 Hz, the minimum number of detected photons in each quadrant needed for reliable tracking is 100. As the APDs saturate at a level of 10^6 counts/s, the useful dynamic range of each SPCM is 250 (6 magnitudes). In order to allow complete freedom in the choice of guide star, a filter wheel consisting of 3 neutral density filters is placed close to the re-imaged focal plane. The filters are in increments of 10^2, allowing us to cover the entire range of guide star magnitudes.

3.2.3 The Infrared Channel

Figure 2 shows the layout of the infrared light path in ROGUE. The relay system is common to both wavelength ranges. The infrared light (1400 nm to 2500 nm) passes straight through the dichroic to form an intermediate image, at the same scale as the visible channel. A magnification of 3 is required to adapt the image scale to the requirements of 3D. This is done by two spherical mirrors, which also image the telescope pupil to the distance required by 3D. The latter constraint requires the use of two optical elements. The position of the telescope pupil is critical to 3D, as it relies on a cold pupil stop within the instrument to block out 300 K blackbody radiation from the telescope structure. The two-mirror off-axis system also provides an opportunity to correct for some of the aberrations introduced by the relay system.

Although it is possible to overcome the limitation of under-sampling the PSF under good seeing conditions as outlined in section 2.2 above, this procedure significantly increases the complexity of the data analysis. For compact objects, the data analysis would be much easier if one simply changed the pixel scale of 3D. The two infrared imaging mirrors provide us with an opportunity to implement this option. A system consisting of two lenses can be inserted in the optical path between the two infrared imaging mirrors to change the scale from $0.5''$/pixel to $0.35''$/pixel. In order to preserve the location of the entrance pupil, these two lenses have to be placed on either side of the pupil image between the two imaging mirrors. Changing the pixel scale also has the unfortunate effect of rendering the cold pupil stop inside 3D too big, thus making it ineffective in blocking out background radiation. We circumvent this by placing a cold stop at the intermediate pupil location, between the two scale change lenses. For eliminating thermal radiation in the K band, it is sufficient to cool this stop to 30 degrees below ambient. The cold stop is placed in a tiny dewar, with the two scale change lenses acting as windows.

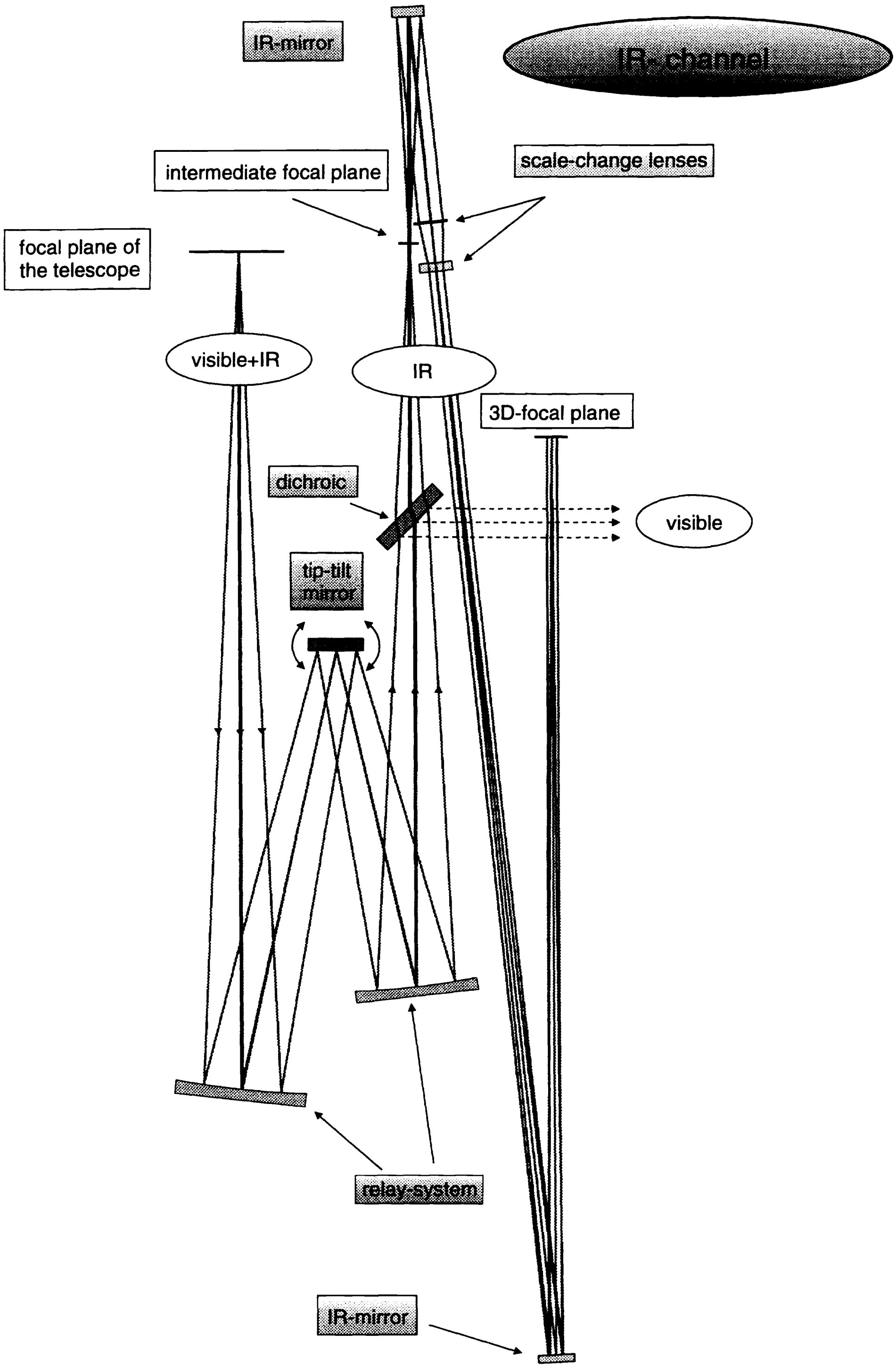

Figure 2: Schematic drawing of the infrared light path through ROGUE. The relay system and dichroic are the same elements as in Figure 1. Rays drawn are different from those in Figure 1.

3.2.4 The Control Software

An IBM compatible PC running Microsoft Windows is used to control the entire instrument. The interaction with the observer is via a virtual instrument interface provided by the LabView package from National Instruments. The control computer is located in the electronics rack near the Cassegrain focus of the telescope. The monitor and keyboard are located in the control room.

The signal from the four SPCMs is fed to a counter/timer card in the computer. The card contains 10 user programmable counters. Eight of these are cascaded in pairs to count the pulses from the four SPCMs. A ninth counter is used as a clock to determine the sampling period. At each rising edge of this clock, the outputs of the counters are down-loaded to a hold register. This operation is performed without any action by the CPU, thus ensuring that the 8 down-load operations are synchronous. The hold registers are read by the CPU when it receives an interrupt, also generated by the same clock edge.

The outputs of the four counters are then co-ordinate transformed and differenced to determine the change in position of the piezo driven tip-tilt mirror. The computed digital signal is fed to a DAC, which generates an analog signal fed to the high voltage piezo amplifier. The voltages applied to the two piezo drivers are also displayed on the console, allowing the user to verify the operation of the system. If the guide star starts to drift outside the range of control of the tip-tilt mirror ($5''$ for ROGUE), the voltages displayed on the console tend to saturate. If this happens, the observer can offset the telescope in the proper direction to maintain the guide star within the control range.

The same computer is also used to control the position of the quadrant detector translation stage. Since this operation does not need to be executed while the system is tracking, CPU speed is not an issue. The motors of the translation stage are controlled via commands sent over the IEEE-488 bus. The filter wheel containing the neutral density filters is also controlled in a similar manner. Data acquisition of the CCD camera is also controlled via the same user interface. The integration time, frame size, on chip binning size etc. may be varied as desired.

4. RESULTS

Figure 3 shows an image of the Seyfert 2 galaxy NGC 1068 in the [SiVI] line at 1.96 μm, obtained with ROGUE and 3D at the 2.2 meter telescope on La Silla, Chile in July 1994. The [SiVI] emission is spatially resolved, the first time that extended [SiVI] emission has been observed in Seyfert nuclei. The [SiVI] line traces coronal gas, presumably ionized by the hot ionizing radiation from the central active galactic nucleus. It is interesting to note that the [SiVI] emission appears coincident with emission in the [OIII] line at 5007 Å , imaged with the Hubble Space telescope. The line is also spectrally resolved, with kinematic structure indicating a velocity gradient from NE to SW across the nucleus. A detailed description of the kinematic features is beyond the scope of this article, see, however, Thatte et al.[4] The high spatial resolution in these data would not have been possible without ROGUE.

During the commissioning run of ROGUE, we were unable to collect data on the extent of image motion, with and without the aid of the tip-tilt system. This was due to technical problems with the recording mechanism of the control software. Consequently, we are unable to present quantitative results of the instrument performance. The problems have now been fixed, and we hope to have performance figures available in the near future.

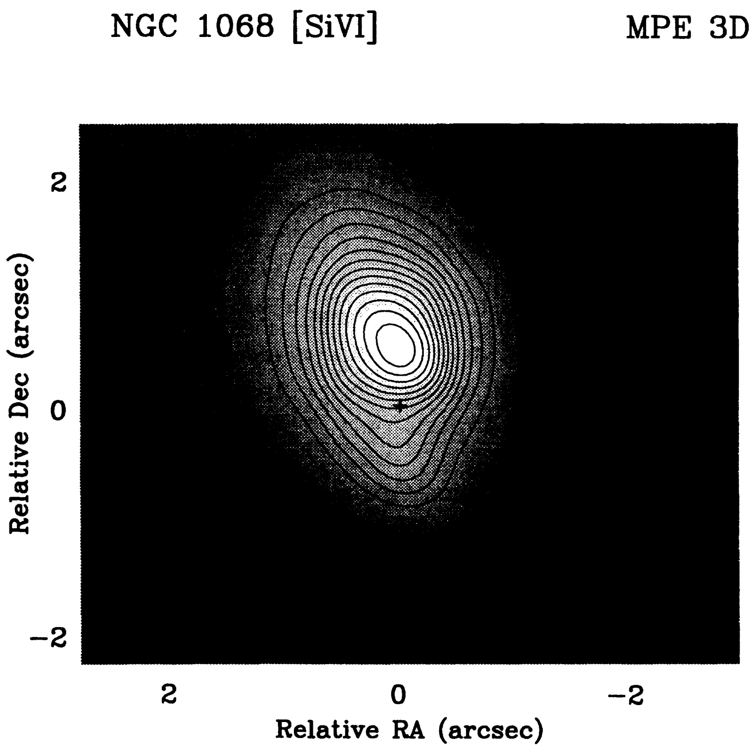

Figure 3: Image of NGC 1068 in the [SiVI] line. The position of the K band continuum peak is marked with a plus. 1″ corresponds to 68 parsecs at the distance of NGC 1068. The gray scale uses a logarithmic look-up table to enhance the extended emission

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