High Resolution Imaging in the Visible from the Ground without Adaptive Optics: New Techniques and Results

Craig Mackay[*a], John Baldwin[b], Nicholas Law[a] and Peter Warner [b]
[a]Institute of Astronomy and the [b]Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge UK, CB3 0HA

Abstract

Many astronomical imaging studies, such as those of weak gravitational lensing, call for better angular resolution than is normally possible from the ground over wide fields of view . For many of these studies astronomers need images which show a consistent point spread function across the field even if this comes at the expense of the ultimate in angular resolution at the centre of the field. Adaptive Optics does not show any prospect of being able to achieve fields of view as large as are needed at visible wavelengths and therefore a new technique of delivering high resolution images from the ground must be developed. Electron multiplying CCDs are available that allow images to be taken at high speed without the usual penalty of read noise. We have developed a new technique called Lucky Imaging which achieves high resolution by selecting the better images from a sequence of images, then shifting and adding each to give a much higher resolution output image. Resolutions in the range 0.1-0.2 arc seconds can be obtained routinely under relatively good conditions on a 2.5 metre telescope working in I band (850 nanometres) and using as much as 30% of the images taken. Even under poorer conditions we find that image selection allows the final resolution to be better than the traditional seeing value by a factor of as much as three. This paper describes the technique and some of the results obtained using this method.

Keywords: high resolution imaging, Lucky Imaging, adaptive optics, spectroscopy

Introduction

It is difficult to exaggerate the contribution to observational astronomy that has been made by the Hubble Space Telescope (HST). Although only 2.5 metres in diameter it has provided near diffraction limited imaging of a great variety of astronomical objects, allowing a remarkable amount of progress towards their understanding. The demand on telescope time together with the limited field of view of the telescope means that wide field surveys with HST resolution are unlikely to be made. In addition the future of HST is now in doubt for a variety of reasons and there are no other space projects underway that offer comparable resolution. Some of these wide field programmes are fundamental to our understanding of the structure of the universe. For example, the study of the systematic distortions of galaxy shapes as the light is bent around concentrations of dark matter in the universe is extremely difficult to carry out from the ground. Distant galaxy diameters are typically only a few arc seconds and the distortions are generally 0.1-0.2 arc seconds at most and often much smaller. Observing such objects with seeing of one arc second from the ground means that high signal-to-noise ratios must be achieved to allow such a small effect be measured. This in turn means that brighter, nearer objects are used for these studies where the amount of weak lensing is even smaller. The consequence is that these studies produce results of worryingly poor significance.

If it was possible to take images from the ground with an intrinsic resolution of 0.1-0.2 arc seconds then such studies would be dramatically easier. Distortions which are also of 0.1-0.2 arc seconds would be much easier to detect and indeed considerably smaller distortions could also be tracked. Tracing the mass distribution in three dimensions through the universe is clearly of the greatest importance for understanding the earlier stages of the universe and how the largest scale structures within universe have evolved since then. We have no other way of detecting this mass distribution than by weak gravitational lensing studies. If ground based astronomers cannot come up with a method of making these measurements then they simply will not be made and we will not know how mass is distributed throughout the universe. All other methods of looking at mass distributions depend on indirect methods such as looking at x-ray emission or

[*] e-mail:cdm@ast.cam.ac.uk; phone +44-(0)1223 337543; fax +44-(0)1223 330804

Sunyaev-Zeldovich microwave absorption effects, both of which are far from unambiguous indicators of the mass distribution in the universe.

High Resolution Imaging from the Ground

A considerable amount of effort has gone into the development of Adaptive Optics techniques as a method of providing high resolution images. There are now a number of systems working around the world but they are very limited in what we can achieve. Under good conditions they are able to provide, particularly in K-band (2.2 microns), near diffraction limited imaging. It is found that the image quality is a very strong function of the angular distance of an object from the reference star used by the adaptive optics system. A detailed study [1] of the size of the isoplanatic patch has been carried out at Paranal, the site of the Very Large Telescope (VLT) operated by the European Southern Observatory. M. Sarazina and A. Tokovinin find that the isoplanatic patch has a diameter of only a few arc seconds in the visible. This is the scale over which the Strehl ratio drops to approximately half its level at the centre position. The consequence of this is that it is extremely difficult to survey a field of more than a few arc seconds with any confidence and even then the most uncertain feature of the image will be its point spread function.

It seems likely that these problems with adaptive optics are fundamental and that even with multi-conjugate adaptive optics (MCAO) techniques in conjunction with laser guide stars, the field over which the point spread function will be adequately defined is likely to be extremely small. A new approach has to be developed if we are to achieve the scientific goals outlined above.

Lucky Imaging Techniques

Suppose we have a telescope with diameter D and seeing conditions that give mean phase fluctuations across the diameter of the telescope so that one radian of phase error occurs on a scale of r_0 (the definition of r_0 used by Fried [2]) so that $D/r_0 < 7$ approximately. This corresponds to imaging in I band (850 nanometres) on a 2.5 metre telescope with seeing of approximately 0.5 arc seconds. The size of the telescope and the wavelength of observation scale, so that $r_0 \propto \lambda^{1.2}$ so that this is equivalent to imaging in K-band (2.2 microns) with a 7.5 metre telescope. If we record images fast enough, the seeing fluctuations are frozen and we find that in a few percent of images the phase fluctuations have become momentarily small enough to give an image that has a much higher than average Strehl ratio. By selecting the best images and combining them by first shifting them so that they are aligned and then adding them we are able to generate an image that much higher resolution than the normal seeing-limited image[3]. The general nature of these images is of a diffraction limited core surrounded by a fainter halo, much as is seen with adaptive optics systems. Further, if the images are sorted into quality bins it is then possible to add in an increasing proportion of the images thereby improving sensitivity at the expense of progressively degrading the resolution. This trade-off between resolution and sensitivity may be carried out after the end of the exposure. The Lucky Imaging technique is described in more detail elsewhere [4,5, 10] and also on the Lucky web site[6] .

In the past Lucky Imaging would have been unacceptably insensitive because of the high readout noise normally associated with running any imaging camera at high frame rates. CCD cameras operating at pixel rates in the megahertz range have a readout noise typically of a few tens of electrons. Running a camera at tens or hundreds frames a second and selecting images by adding many frames together greatly reduces the sensitivity of the system. The aggregate readout noise is equal to the square root of the number of frames used times the readout noise level for a single frame. Recently, however, CCDs have been developed with an internal gain mechanism that allows them to be read at high pixel rates (up to 35MHz) with negligible readout noise [7,8] . The way these detectors work has already been described [8] .It is enough here to say that these devices work in essentially the same way as normal CCDs except that their readout noise is reduced by this gain mechanism to negligible levels. The only negative feature about these devices is that at high signal levels (>1 photon per pixel per frame) their quantum efficiency is effectively halved by the stochastic nature of the gain mechanism [8,9] . When working at low photon rates, however, as is often the case with fast frame rates this problem is much less significant since it is possible to operate these devices in a photon counting mode.

The development of EMCCDs has meant that Lucky Imaging can be used without the usual noise penalty and large numbers of frames can be co-added without a corresponding increase in the background noise level. We have developed a camera that allows us to try out many of the basic techniques associated with Lucky Imaging and have used this camera on several occasions on the Nordic Optical Telescope (NOT) on La Palma, Canary Islands. In the remainder of the paper we will discuss the results obtained on these observing runs.

Lucky Imaging on the NOT.

A camera was built based on an existing CCD controller (the AstroCam 4100 Capella controller) and operated at 4MHz pixel rates. We have used a variety of EMCCDs manufactured by E2V Technologies Ltd (Chelmsford, UK) and called L3CCDs by them, including the CCD 65 (2002), the front illuminated CCD 87 with 512 x 512 pixels each 16 microns square pixels (in 2003) and the CCD 97 which is back illuminated and with the same format as the CCD 87, (2004). With this camera system the data are taken directly into the computer memory and then saved at the end of the exposure onto a high-speed disk system. At the end of the night this fast RAID array disk drive is then backed up onto conventional IDE disk drives for archive purposes. The camera can be used in a variety of formats and frame rates ranging from a hundred frames per second (with a format of 100 x 182 pixels), 512 x 176 pixels at about 30 frames per second and 512 x 512 pixels at 12 frames per second. The camera was usually run for about 80 seconds (by which time the computer memory was full) giving typically 10,000, 3000 and 1000 frames in each of these three formats respectively. Because there was no real time processing the system was relatively inefficient and only relatively short runs were possible. With the exception of the most recent run in 2004 the conditions were generally good with seeing between 0.5 and 1.0 arc seconds. In 2004 the seeing was very much poorer, seldom being better than one arc second and one occasions as poor as 4 arc seconds. Most of the work was carried out in I band. Many different types of astronomical object were observed with a variety of frame rates. What is described here is a summary of the results as seen from the point of view of an instrument developer rather than as an astronomer.

Lucky Imaging with $D/r_0 < 7$.

Under conditions of relatively good seeing there is a finite chance that the image of a bright reference star when imaged at high speed will consist of a single bright speckle (references). Frames taken at high speed may be graded on the basis of the sharpness of the central spike in the image profile and then shifted into registration and co-added to give an image with an angular resolution of 0.1 arc seconds when only the best few percent of the images are used. There is a considerable amount of variation in the full width half maximum (FWHM) on very short timescales seen in virtually all runs. Examples of this are shown in figure 1.

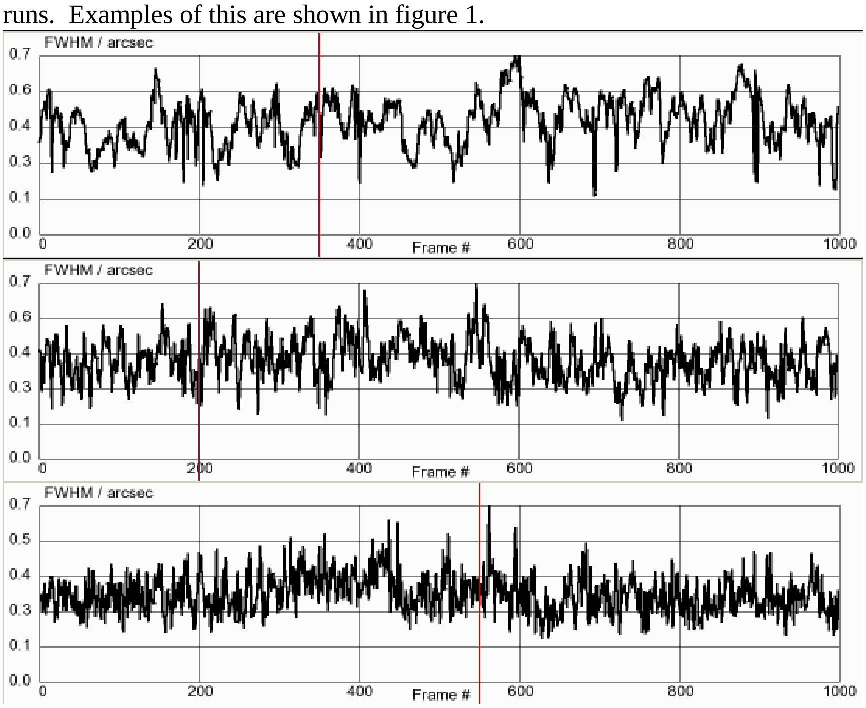

Figure 1: Plots of the distribution of Full Width Half maximum (FWHM) for runs of 1000 frames at frame rates of 100Hz (top), 33 Hz (middle) and 12 Hz (lower). They show that at the rate of 100 Hz there is a lot of frame-to-frame correlation and progressively less at the slower frame rates. This implies that a frame rate of 100 Hz is faster than is really needed for Lucky Imaging.

All these image runs were taken under conditions that gave a conventional seeing measurement of 0.6 arcsec. These plots show the instantaneous frame FWHM and so do not show any component of image wander that would be removed by a tilt-tip system, or in our case, the shift-and-add procedure.

The precise angular resolution obtained depends on the fraction of images used. The resolution is degraded as more images are incorporated by the overall sensitivity but the limiting magnitude of the images is improved considerably. This is shown in figure 2.

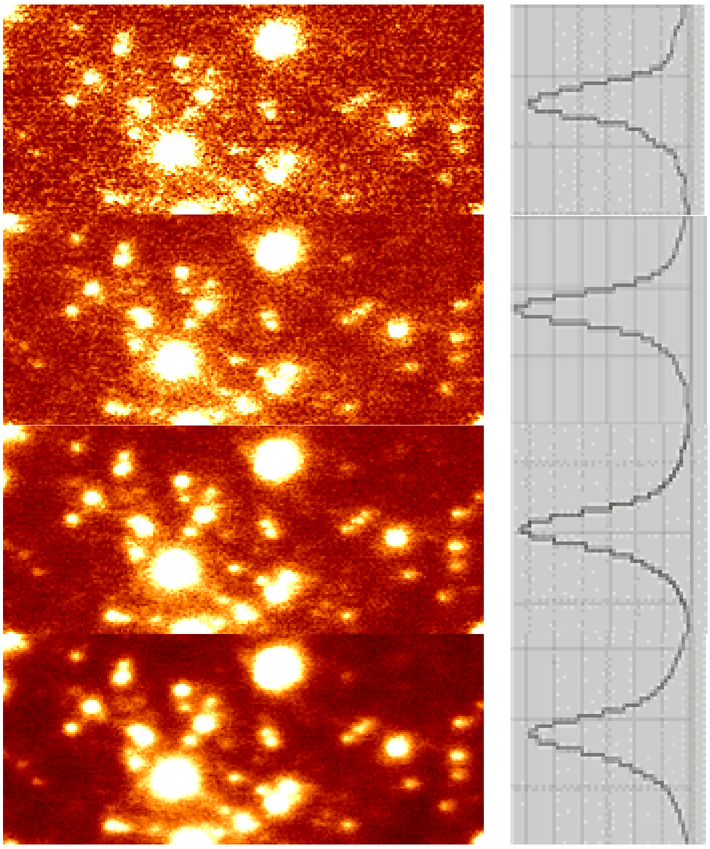

Figure 2: Images selected from a single run of 1000 frames at 12 Hz frame rate are shown for selections from top to bottom of the best 1%, 3 %, 10% and 30% respectively.

As the percentage of frames used increases the sensitivity of the imaging increases at the expense of the image resolution which worsens from top to bottom at 0.12, 0.13, 0.14 and 0.17 arcsec FWHM.

Even with 30% selection the images are of dramatically better resolution than the 0.6 arcsec that were obtained during a normal long integration.

The CCD that we used is relatively small (512 x 512 pixels) and the magnification used gave 25 pixels per arc second and therefore a maximum field of view of only 20 x 20 arc seconds. Running in full frame mode gave a frame rates of only 12 frames per second. Faster frame rates were possible but only by running in smaller formats. Earlier work (references) used an off-axis mirror to allow stars that would normally be too far apart to be observed simultaneously in order to delineate the size of the isoplanatic patch. These showed that the Strehl ratio of stars close to the reference star was reduced by a factor of two at an angular distance of about 25 arc seconds from the reference star. This isoplanatic patch diameter of about 50 arc seconds is approximately 10 times the diameter of the isoplanatic patch as determined by the VLT studies mentioned earlier. The selection of the best images corresponds to selecting those moments with the smallest phase errors. The angular decorrelation which comes from looking at objects away from the reference star will be minimised under these conditions. We are therefore effectively selecting images that have a large isoplanatic patch size when we select images that have the best Strehl ratio. We also believe that the isoplanatic patch size of about 50 arc seconds diameter of may be underestimated in these tests because of residual optical aberrations in our setup for objects more than 15 arc seconds from the reference star.

The Lucky Imaging technique depends on a reference star being present in the image in order to let us measure the momentary image quality. This reference star needs to have an adequate signal-to-noise to allow us to measure its Strehl ratio. We find that we can use reference objects as faint as magnitude ~ 16.5 (I band) when using a front illuminated CCD. We expect to be able to reach approximately one magnitude fainter when using a thinned CCD. These reference star magnitudes are much fainter than are normally usable by adaptive optic systems. This is because we use a reference star detected with the whole diameter of the telescope rather than , for example, only one element of a Shack Hartmann wavefront sensor. The ability to use faint reference stars is important because it greatly increases the number of fields that one can observe with the natural guide star. In addition, this technique allows in principle the use of several stars within the field even though each may be individually fainter than this above limit. With a large isoplanatic patch size in many cases we will find that using multiple reference stars is convenient.

Our limiting magnitude in these images is already ~ 19 magnitude in I band using 80 seconds on-sky and 10% selection of frames taken at 12 frames per second with 0.6 arcsec seeing. We predict that we can reach magnitudes as faint as I ~ 24.5 in one hour of on-sky time using a thinned CCD to give images with a full width half maximum of 0.14 arc seconds. In principle we should be able to use the best few percent of images which are close to being diffraction limited to provide an instrumental transfer function that may be used to deconvolve the slightly less good images. These may then be added into the sum to increase sensitivity without the corresponding reduction in resolution that would otherwise occur.

Lucky Imaging with D/r_0 >>7

We also find that even under conditions of poor seeing there are considerable variations in the full width half maximum of images taken relatively quickly. Examples of a run taken when the seeing was typically 1.4 arc seconds is shown in figure 3.

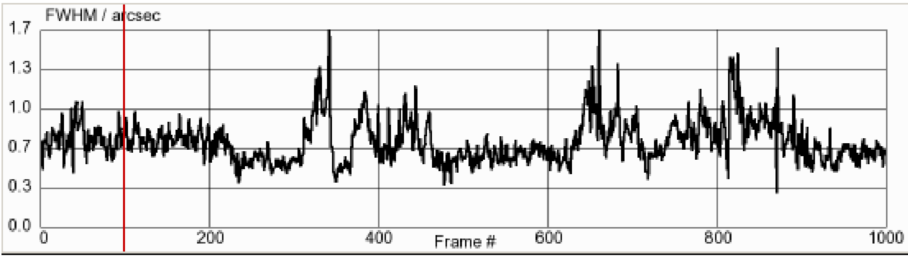

Figure 3: A plot of the FWHM of a run of 1000 images at 12 Hz under relatively poor seeing conditions (1.4 arcsec)

As before, it is clear that the image resolution will be greatly improved if we restrict our selection of images to those which are much better than average. Again we find that obtained a considerable range in image quality depending on the fraction of images that we use even under these relatively poor conditions. This is shown in figure 4.

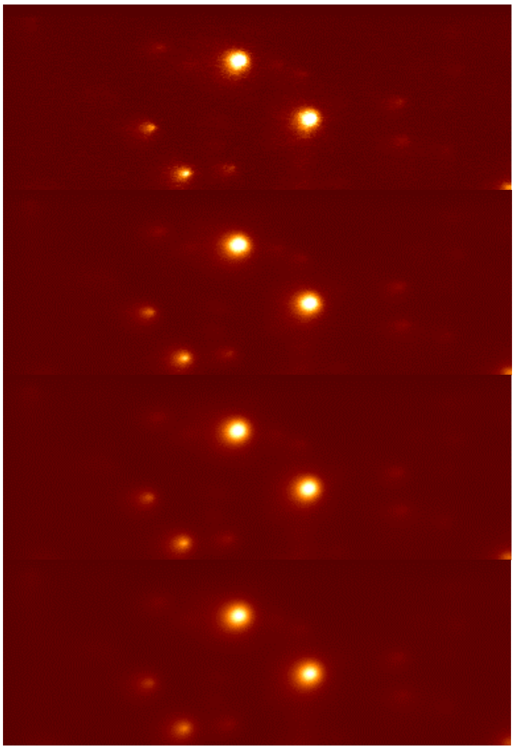

Figure 4: A series of images taken from a single run of 1000 frames at 12 Hz frame rate taken under relatively poor observing conditions with seeing measured at about 1.4 arcsecs. The images were obtained by selecting the best 1% , 5%, 20% and 50% of images (in order from top to bottom), giving image resolutions at FWHM of 0.27 , 0.38, 0.43 and 0.50 arcsecs.

They show that even under these conditions where the proper Lucky Imaging is not working (i.e. when a single speckle is essentially never obtained) it is possible to gain a considerable improvement in image resolution by image selection.

Wide Field Lucky Imaging

Although we find that the typical size of the isoplanatic patch under conditions of relatively good seeing is just under one arc minute we should be able to undertake wider field surveys by using an array of electron multiplying CCDs. How this might be done in shown in figure 5.

Figure 5: A schematic of how an array of EMCCDs might be arranged to allow coverage of wide fields of view.

The EMCCDs are frame transfer so only the shaded section of each is light sensitive. They are arranged so that each sensitive area is spaced from its neighbour by just under one width horizontally, and just under two heights vertically to ensure full field coverage. This requires the telescope to be pointed to six separate positions in the sky for complete are coverage.

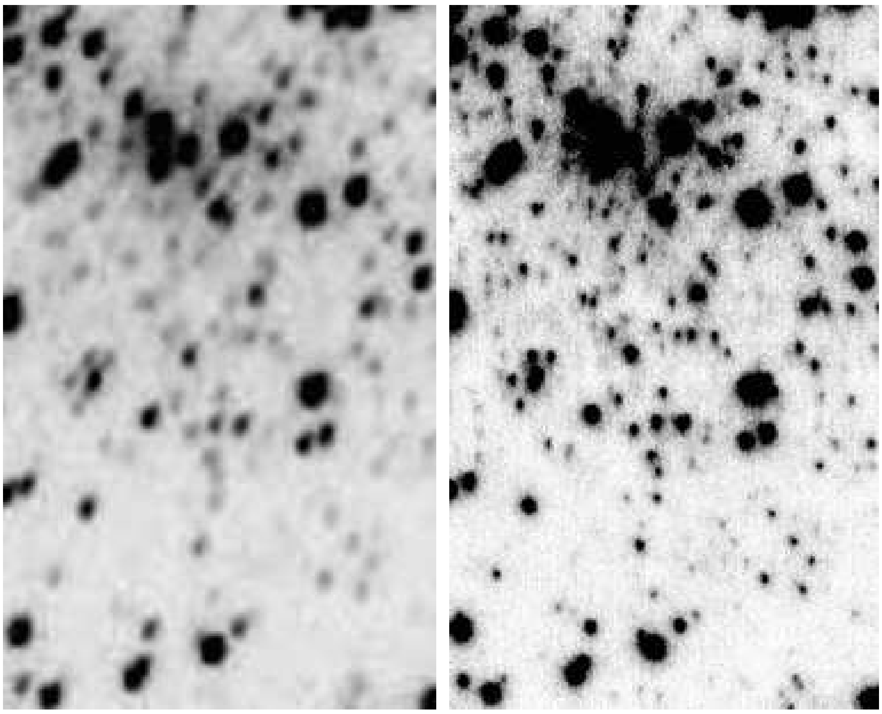

Figure 6: Images of part of the core of the globular cluster M15 when the seeing was about 0.6 arcsec. The left-hand one was taken with the standard CCD camera on the NOT telescope on La Palma which has 0.16 arcsec per pixel, and the right-hand one is part of a mosaic of selected images that show an image resolution over the field of about 0.14 arcsec.

Each of the Lucky Imaging images were taken from a 100 frame run at 12 Hz frame rate and 10% selection.

If we imagine covering the focal plane of the telescope with an array of these devices then each may be run independently, giving its own moments of excellent seeing and allowing a high resolution representation of each piece of sky to be built up independently. At the end of the run the telescope is moved so that with a total of six sky positions it is possible to observe every part of the field. These images, one from each detector in each of the six telescope pointings allow a wide field image to be constructed from a mosaic of these images.

We have carried out tests to demonstrate that this is quite practical using our single CCD detector running at 12 frames per second at a series of positions in the globular cluster M15. Figure 6 shows two images, the lefthand one taken with the resident general purpose CCD camera of the NOT telescope. It uses a SITe 1024 x 1024 CCD at a scale of six pixels per arc second. The right-hand image is part of a mosaic taken with our Lucky Imaging camera just a few minutes after the picture on the lefthand side was taken. The improvement in resolution is dramatic, with the seeing indicated by the standard camera of 0.6 arc seconds been reduced to approximately 0.14 in this image taken with 10% selection. The quality of these images is remarkable particular a when we remember that the scale used of 0.04 arc seconds per pixel does not adequately sample the Airy disk and a frame rate of 12 frames per second is much lower than we would ideally like to use. It is almost certain that a faster frame rate would have reduced the image smearing and improved the Strehl ratio of these images.

Lucky Spectroscopy

Wide field spectroscopic surveys may be carried out by using an objective prism or grating. The light from the entire field is dispersed stretching out each image into a small, relatively low resolution spectrum. The limiting sensitivity of objective spectroscopy is set by the fact that each spectral resolution element is seen against the broadband night sky emission. Using a Lucky image selection technique each spectrum may be selected to be much narrower than would normally be and therefore to improve sensitivity significantly when compared with conventional objective spectroscopy. Because the images are sharper one may use a lower dispersion further improving sensitivity. We have carried out a few observations using a transmission grating as the objective dispersing element. An example of an image taken under relatively poor conditions of seeing (approximately 1.5 arc seconds) is shown in figure 7.

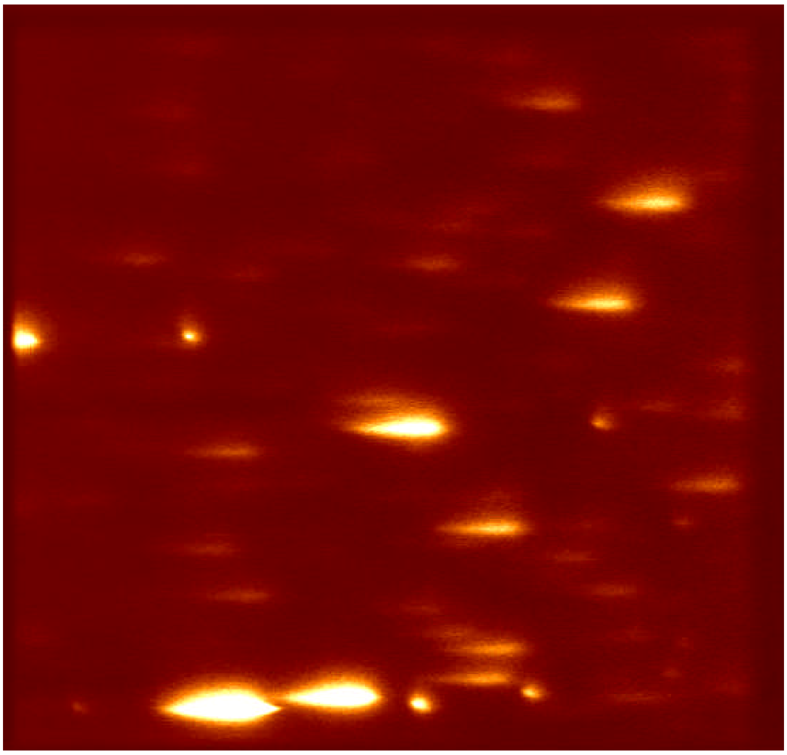

Figure 7: An image of the core of the globular cluster M3 through an objective grating. Each star has a faint zeroth order component that was used as the reference star, and the dispersed light spread out to the left.

The image was a 10 % selection from a 1000 frame run at 12 Hz frame rate under relatively poor seeing conditions of 1.5 arcsec.

With the grating we are able to use the zeroth order image which is undispersed as the reference object. With Lucky Imaging under good conditions the angular resolution may be improved by a factor of approximately five. With Lucky spectroscopy that is sky background limited the sensitivity should be improved by a factor of approximately 25 (more than 3.5 magnitudes). This broadens considerably the attraction of Lucky image selection techniques for carrying out wide field spectroscopic surveys.

Conclusions

We have demonstrated a new technique that allows wide field imaging in the visible from the ground with a resolution dramatically better than is possible by any other method, a resolution that is close to that achieved by the Hubble Space Telescope. Despite the considerable amount of work and money devoted to adaptive optics it is still the case that no images have been produced in the visible with a resolution close to that of the Hubble Space Telescope from the ground. This has been achieved here at very low cost and indeed the ease with which the method works suggest it should be applied widely. It is a technique that offers the possibility for the first time of carrying out high resolution imaging from ground-based telescopes that will let us trace the distribution of dark matter in universe.

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