INFRARED ARRAY DETECTORS: PERFORMANCE AND PROSPECTS

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ABSTRACT: Infrared array detectors, like silicon CCDs a decade before, have revolutionized infrared astronomy. The quality and performance of the current generation of devices has already allowed astronomers to obtain infrared images at wavelengths out to 2.2 microns which are as deep as the best CCD images. High resolution infrared spectroscopy is now a reality and ground-based imaging to 35 microns has been achieved. Several classes of low-noise infrared array detectors with formats of 256 x 256 pixels are now in routine use, and developments are under way which will produce detectors of 1024 x 1024 pixels (for the near IR) within the next year. This paper will briefly review the state-of-the-art and compare and contrast the properties of available arrays. Progress in the field is illustrated with recent near infrared photometry obtained with a new two-channel imaging system developed at UCLA.

1. INTRODUCTION

Infrared wavelengths provide a unique and powerful window on the Universe for the study of many things, from molecular clouds to protogalaxies. Relatively cool objects, such as dwarf stars or giant planets radiate strongly in the IR, and less extinction means that infrared wavelengths allow us to "see" inside dusty, optically-opaque star-forming regions.

Unfortunately, progress at ground-based observatories has been hampered by the nature of the technology available for the detection of IR photons. Until the mid-eighties, only simple "single-element" photovoltaic (PV) or photoconductor (PC) detectors were available. The only way to form an "image" of a scene was to "scan" the image across the detector by pointing the telescope systematically at numerous positions in a grid of coordinates on the sky. The technique was prone to errors and provided little opportunity to "integrate" signal at each position.

In contrast, optical astronomy has benefitted from the Charge-Coupled Device (CCD), which was introduced into astronomy in 1976 only six years after it was invented by Boyle and Smith at Bell Labs (the story of CCDs in astronomy is described in McLean 1989). Because of its semiconductor band-gap, the silicon CCD is not sensitive to wavelengths longer than 1.1 microns. Stimulated by military applications, however, many one- and two-dimensional infrared imaging detector technologies were developed and classified around this time, but none were really suitable for the much lower backgrounds and non-real-time or "staring" applications of astronomy. Fortunately, in the mid-eighties, infrared focal plane "array" detectors developed specifically for astronomy came into operation. The first arrays had formats of 64 x 64 pixels or less, but this was thousands more elements than before!

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The impact of the introduction of infrared array detectors has been staggering. I reviewed the field in an article (McLean 1988) following the "turning-point" conference entitled "Infrared Astronomy with Arrays" held in Hilo, Hawaii in 1987 while I was still with the UK Infrared Telescope observatory on Mauna Kea. Only six years later, 300 astronomers and many representatives from the IR detector industry, gathered at my new home, the Departments of Astronomy and Physics at UCLA, from July 18 - 22, 1993 to attend a similar conference entitled "Infrared Astronomy with Arrays: The Next Generation" (McLean 1994). They saw spectacular results from numerous infrared cameras and spectrometers, most using the latest 256 x 256 (65,000) pixel arrays, and heard the plans for the development of 1024 x 1024 pixel arrays within two to three years. This summer, July 1994, Klauss Hodapp at the University of Hawaii, obtained the first images with a 1024 x 1024 HgCdTe array manufactured by Rockwell International. Given the difficulties of this technology, from one to one million pixels in such a short period of time is both amazing and exciting!

2. INFRARED ARRAY DETECTORS

2.1 Current Technology

Several companies have developed IR focal plane arrays which have been used successfully in astronomy applications, including Aerojet Electrosystems, Amber Engineering, Cincinnati Electronics Corp., Hughes-SBRC, Kodak, LETI-LIR, Mitsubishi and Rockwell International; most of these are in the USA.

Infrared-sensitive materials currently in use are summarized in Table 1. The principal materials are PtSi, HgCdTe and InSb for wavelengths less than five microns and doped silicon (e.g. Si:As, Si:Sb) for the 10 - 20 and 10 - 30 micron regions respectively. Work is in progress to develop doped germanium arrays and silicon bolometer arrays for even longer wavelengths. Other papers to be presented at this conference will provide more details on each of these detector options. In general, infrared detectors are formed either from reversed-biased pn junctions (InSb and HgCdTe photodiodes), Schottky-Barrier junctions (PtSi) or Impurity Band Conduction (also known by various trade names such as BIBs, BIBIBs) in doped silicon or germanium.

Currently, the best available arrays for infrared astronomy include the following:

a) 256 x 256 pixel HgCdTe array from Rockwell International Science Center. This device is also known as the "NICMOS 3" array because it was developed for the NASA/University of Arizona Near Infrared Camera and Multi-Object Spectrometer, a second-generation instrument for the Hubble Space Telescope (PI: Rodger Thompson). Dr. Kadri Vural at Rockwell has been a strong supporter of astronomy programs. These devices have quantum efficiencies from 40 - 60% from 1 - 2.5 microns, readout noise of 40 electrons rms, and dark currents of less than one e/s/pixel when operated at 77° K (liquid nitrogen). The pixel size is 40 microns and the charge storage capacity is about 200,000 electrons.

b) 256 x 256 pixel InSb array from the Hughes Santa Barbara Research Center (SBRC). Dr. Alan Hoffman at SBRC was one of the first people to recognize the potential of IR arrays for astronomy and he has pioneered the development of specialized astronomy arrays for many years. A "low background" version of this array is also being developed for the NASA Space

TABLE 1

Current detector materials and array formats

Material	Symbol	Cut-off Wavelength	Type	Formats
mercury-cadmium -telluride	HgCdTe (55%Hg)	2.5 microns	pn	256 x 256 1024 x 1024*
indium antimonide	InSb	5.3 microns	pn	256 x 256 1024 x 1024*
platinum silicide	PtSi	~4 microns	Schottky	256 x 256 640 x 480 512 x 512
extrinsic silicon	Si:As	23 microns	PC,IBC	58 x 62, 96 x 96 128 x 128
	Si:Sb	29 microns	PC,IBC	256 x 256
extrinsic germanium	Ge:Ga	113 microns	PC,IBC	*

Notes: * under development

Infrared Telescope Facility (SIRTF), with Giovanni Fazio at the Harvard Smithsonian Center for Astrophysics and Judith Pipher and Bill Forrest of the University of Rochester playing major roles. These devices have quantum efficiencies from 70 - 80% from one to five microns, readout noise of 60 electrons rms, and dark currents of less than one e/s/pixel when operated at about 30 K. The pixel size is 30 microns and the charge storage capacity is about 200,000 electrons.

c) Silicon IBCs are available in up to 256 x 256 formats from Rockwell International (Anaheim, USA) and Hughes-SBRC (Carlsbad, USA), and in smaller formats from LETI-LRI (France). Different versions are possible depending on whether the application is ground-based or space-based, i.e. large well-depth or modest well-depth. To date, the largest format actually used at a telescope is 128 x 128 (see Herter 1994 for a review). These devices are always background limited for imaging.

d) Platinum silicide arrays from Hughes (256 x 256 pixels), Kodak (640 x 480 pixels) and Mitsubishi (512 x 512 pixels) have all been used in astronomy applications. These devices are attractive because they have good uniformity and low noise, but they have inherently very low quantum efficiencies (a few %) and hence their range of applications is limited to wide-field surveys of relatively bright sources. Recent work in Japan is aimed at increasing the QE by almost a factor of ten (see paper by Ueno 1995).

Infrared array detectors are NOT based on the charge-coupling principle of silicon CCDs

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(McLean 1993). Instead, the role of detecting IR photons is separated from the role of multiplexing the resultant electronic signal generated in each pixel and relaying it to the outside world. To achieve this, each device is made in two parts, an upper slab and a lower slab. In the upper piece is the IR-sensitive layer which is effectively subdivided into a grid-like pattern of pixels by the construction of tiny junctions. The lower slab is made of silicon and contains a matching grid of "unit cells" in which the infrared detector is connected to the input gate of a FET source-follower and there is also a "reset" FET connected to the same node. Interconnecting the two slabs are tiny columns of indium, called "bumps". Either the upper slab is constructed on an IR-transparent substrate such as sapphire or it is physically thinned and backside illuminated. This construction is known as a "hybrid". The output from each unit cell source follower is connected to an output bus and a final output source follower by a system of shift registers which can address each pixel in turn.

The electronics required to operate IR arrays is very similar to that needed for CCDs, e.g. a small number of clocked lines, level shifters, a few dc bias lines, low noise preamplifiers and an A/D system of typically 14 - 16 bits. Infrared arrays usually have multiple outputs and, because of the much higher background levels, the maximum integration time becomes very short at longer wavelengths, i.e. the bandwidth of IR electronics systems tends to be higher than for CCDs.

2.2 Charge Storage and Collection

In an infrared array detector the absorption of a photon with a wavelength shorter than the cut-off wavelength generates an electron-hole pair. The electrons are collected at the pixel location by electric fields applied either internally or externally or both. For example, in the current generation of InSb and HgCdTe arrays, the field is produced by a reverse-biased pn junction and the depletion region acts like a capacitor which becomes progressively discharged as photogenerated charges accumulate. Since the storage capacitance is at least partially a function of the changing reverse bias, then a small non-linearity is introduced. The effect is always less than 10% worst case and it is smooth and easily corrected. A voltage change applied to the input of the silicon FET is "followed" at the output. The output voltage can be sampled without affecting the input signal, which means that these arrays offer opportunities for noise-improvement using multiple non-destructive sampling. In addition, when the detector is fully de-biased there is no charge "bleeding", but integration ceases and the pixel output is no longer linear with photon flux, i.e. the pixel is saturated. In general there is always a trade-off to be made in selecting the effective pixel capacitance; the larger the capacitance the greater the charge storage or integration capacity ($Q = CV$), but the greater the noise-equivalent charge.

2.3 Detector Properties

In general, there is a very strong, wavelength-dependent, "background" flux of photons comprising thermal emission from the telescope and atmosphere, and non-thermal emission from the night sky - mostly in the form of solar-induced photochemical line emission from the OH radical in the upper atmosphere. Each detector also exhibits an intrinsic "dark current" when not illuminated due simply to thermal excitation of electrons within the semiconductor. This effect can be reduced by many orders of magnitude (to about one electron/s/pixel) by cooling the detector to a very low temperature. For short wave HgCdTe arrays, liquid nitrogen is sufficient (77° K), but for InSb it is necessary to go down to about 30° K (usually with a dual liquid helium/liquid nitrogen system or, in more modern instruments, with a closed-cycle refrigerator). Even lower temperatures are needed for BIB arrays and again liquid helium (4° K) is used. Infrared array detectors also exhibit readout noise (R) like CCDs. A typical value for all the 256 x 256 devices mentioned in this paper is 50 electrons rms, but special multiple non-destructive sampling techniques have achieved noise values as low as 20 electrons.

So far, the InSb detectors have achieved the best quantum efficiencies, followed by the HgCdTe arrays and then the IBC devices. Currently available platinum silicide detectors have very low quantum efficiency (about 2%) at the wavelengths of interest, but they also have the lowest readout noise. Most of the recent devices achieve a good, average non-uniformity over the array of 10% (or better) of the mean. In general, the InSb devices are somewhat more uniform than the HgCdTe arrays and the PtSi arrays are best of all.

2.4 Prospects for Larger Formats

Formats of 256 x 256 pixels are now in routine use for precision astronomical cameras and spectrometers. Astronomy arrays with 1024 x 1024 pixels are currently under development in the USA using both HgCdTe (Rockwell) and InSb (SBRC). The Rockwell project (called HAWAII) is funded by the University of Hawaii and the US Airforce, whereas the SBRC project (called ALADDIN) is funded by the National Optical Astronomy Observatories (NOAO) and the US Naval Observatory (USNO). The current status of these programs is as follows.

The HAWAII 1024 x 1024 array has 18 micron pixels and four outputs configured as four 512 x 512 quadrants. One working device was delivered to Hawaii in time for the comet Shoemaker-Levy collision with Jupiter in July 1994. According to Klauss Hodapp, additional work will be required to establish a stable production line of these chips.

The ALADDIN InSb array has 27 micron pixels and 32 outputs, eight per 512 x 512 quadrant. Al Fowler and Ian Gatley of NOAO report that yields of the new multiplexers have been very good. Hybridization is in progress and results are expected within a few months.

Typical "science grade" devices are costly and range from \$60 K to \$100 K for current HgCdTe and InSb 256 x 256 devices. This is expensive compared to silicon CCD technology and platinum silicide IR technology. However, both of the 1024 x 1024 devices will be even more costly with estimates ranging from \$150 K to \$250 K at the present time. Clearly, each detector has advantages and disadvantages, and each must be carefully investigated for its anticipated application.

3. ASTRONOMICAL PERFORMANCE OF IR ARRAYS

Infrared cameras have improved considerably in the past six years. The original 62 x 58 InSb arrays, for instance, had a readout noise of over 400 electrons rms in correlated double sampling mode. Remarkably, this was still sufficiently low to permit background-limited imaging in all broad bands from one to five microns. Since the QE was very high and the actual background per pixel was much less than in old aperture photometers, the result was a huge increase in sensitivity.

Typically, the most recent cameras have a throughput (transmission x quantum efficiency) of 30% or more, readout noise of 40 electrons rms or better, many more pixels, and dark currents which are sufficiently low to allow efficient spectroscopy with resolving powers up to R = 20,000. Many more applications to spectroscopy will be coming in the future which, in itself, is a testament to this technology. Good flatfielding to levels comparable with silicon CCDs, and good stability has led to photometry with IR arrays to levels which are as deep as the best silicon CCDs.

To illustrate progress I will describe some results with a new, unique, twin-channel, cryogenic IR camera system developed at the UCLA Infrared Imaging Detector Lab. The UCLA camera contains a very efficient (96%) dichroic beam-splitter which allows two near IR bands to be observed simultaneously. Light collected by the telescope is first collimated, then separated into two beams by the dichroic and finally re-imaged onto a focal plane array. In the short wave band (1 - 2.5 microns) a 256 x 256 HgCdTe array from Rockwell International is used, while in the long wave band (2 - 5 microns) a 256 x 256 InSb array from Hughes-SBRC is employed. A choice of dichroics allows the so-called atmospheric "K" window, which is a transparent band from 2.0 - 2.4 microns, to be delivered to either channel for cross-calibrations. Each channel is a fully independent, general purpose camera in its own right, with a selection of broad and narrow band filters, grisms (R = 500) and polarizers. On the 3-m UCO telescope at Lick Observatory, the pixel size is 0".7 and the field of view is 180" x 180". Measured backgrounds at K' (1.95 - 2.30 microns) are about 13.1 magnitudes per square arcsecond and throughput is about 30% per channel. (For more details see McLean et al. 1993 and McLean et al. 1994.)

First Light was obtained on the UCO 3-m telescope in June 1993 (McLean 1994). Since the two channels are completely independent, J and H exposures can be "nested" within a longer K exposure. The choice of dichroics means that it is also possible to nest J, H and K exposures inside an L-band exposure. The three sigma, one minute limiting magnitudes for point sources under typical seeing conditions (synthetic aperture of 3.0" diameter) is K' = 18.0 and, simultaneously, J = 19.7. The camera is very powerful for survey work.

Fig. 1 shows an image of the central 7.6 x 7.6 arcminutes of the Local Group spiral galaxy M 33; the image is a composite of J, H and K exposures. Using DAOPHOT, McLean and Liu (1995) have obtained three-color photometry for over 1700 stars, and have separated the bulge and disk components. A (J-K) v K color-magnitude diagram is shown in Fig. 2, and for comparison, typical loci are shown for giant stars in Baade's window and in well-known globular clusters in our own galaxy. The arrays are good enough to allow absolute photometry to a few percent and relative photometry to a few tenths of a percent on sufficiently bright sources. More details are given in McLean and Liu (1994).

Photometry of much fainter objects is also now feasible. Teplitz and McLean have obtained deep JHK photometry of over 150 galaxies in two dense clusters at redshifts of 0.4, Abell 370 and Cl0024+16, both of which exhibit gravitational arcs and arclets. Fig. 3 shows an image of Abell 370 and Fig. 4 gives the derived photometry of the galaxies. More details are given in the poster by McLean, Liu and Teplitz (1995) at this symposium. Only five years ago, good three-color photometry to this depth on so many faint objects would have been a real chore.

As the 1024 x 1024 arrays become available, we will see more and more emphasis placed

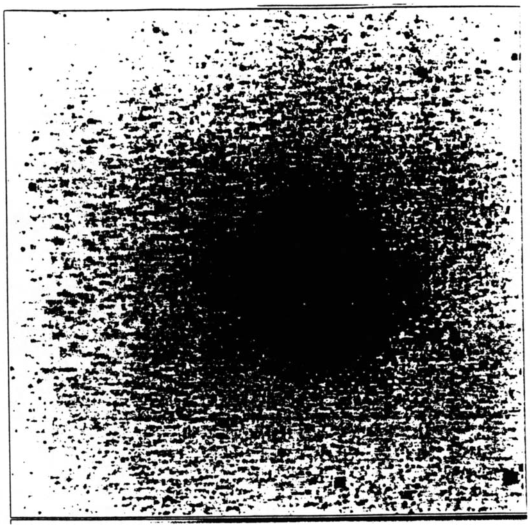

Fig. 1. A JHK composite image of the center of M 33. The field is about 7.6 x 7.6 arcminutes and was obtained by the UCLA twin-channel camera on the 3-m Shane telescope on Mt. Hamilton.

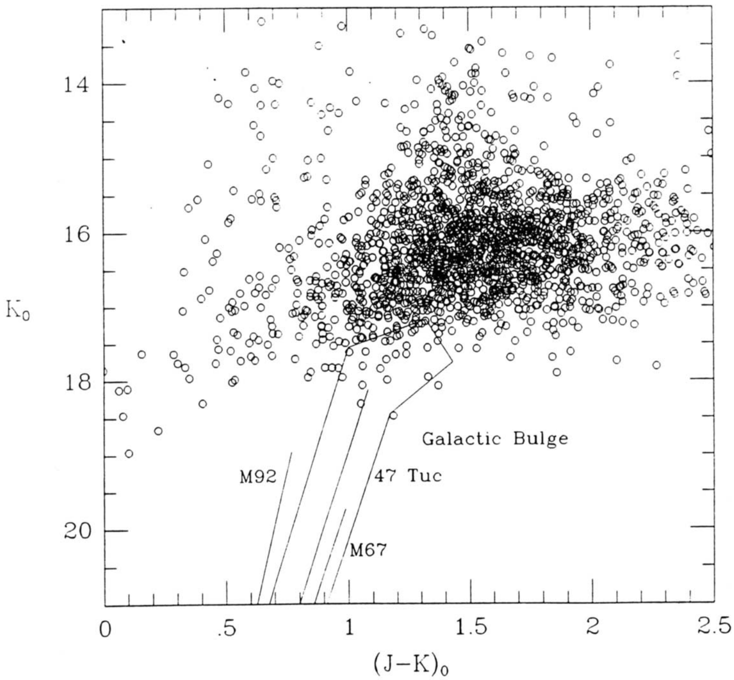

Fig. 2. A (J-K) v K color magnitude diagram of 1700 stars in the central regions of M 33 demonstrating the presence of a population more luminous than any in our galaxy.

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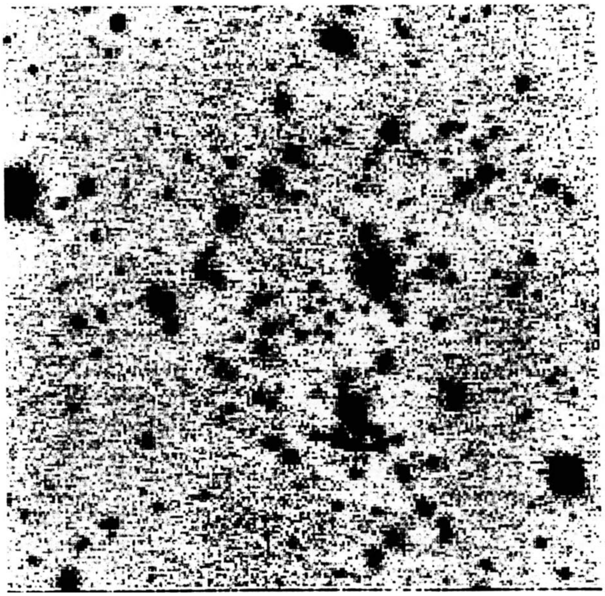

Fig. 3. A JHK composite image of the cluster Abell 370 at a redshift of 0.37. The total exposure time was 90 minutes and the completeness limit is about K = 18.

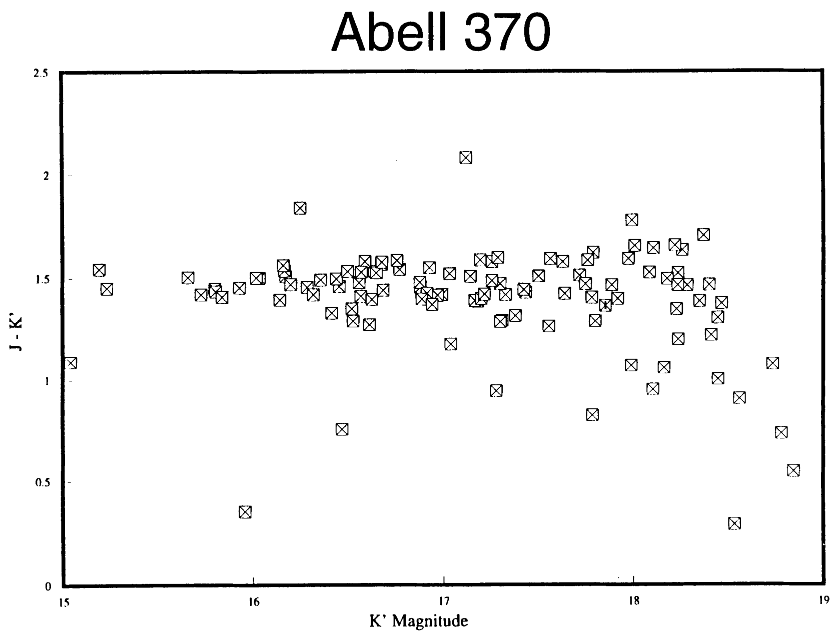

Fig. 4. A color-magnitude diagram for over 150 galaxies in the cluster Abell 370.

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on the application of these IR detectors to spectroscopy. These are exciting times for infrared astronomy.

REFERENCES

Herter, T. 1994 in Infrared Astronomy with Arrays, I. McLean, ed., Kluwer Academic Pub., Dordrecht, p. 409

McLean, I. S. 1988 Sky & Telescope 75, No. 3, 254

McLean, I. S. 1989 Electronic and Computer-aided Astronomy: from eyes to electronic sensors, Ellis Horwood Ltd., Chichester, UK

McLean, I. S. 1993 Proceedings of the IV Canary Islands Winter School; Infrared Astronomy, A. Mampaso, M. Prieto and F. Sanchez, eds., Cambridge University Press, p. 336

McLean, I. S. 1994 Infrared Astronomy with Arrays: the Next Generation, I. S. McLean, ed., Kluwer Academic Publishers, Dordrecht

McLean, I. S., Becklin, E. E., Brims, G., Canfield, J., Casement, L. S., Figer, D. F., Henriquez, F., Huang, A., Liu, T., Macintosh, B. and Teplitz, H. 1993 Proc. SPIE, Vol. 1946, Infrared Detectors and Instrumentation, A. M. Fowler, ed., p. 513

McLean, I. S. and Liu, T. 1995, submitted to ApJ.

McLean, I. S., Liu, T. and Teplitz, H. 1995 in IAU Symposium No. 167, New Developments in Array Technology and Applications, A. G. D. Philip, K. A. Janes and A. R. Upgren, eds, Kluwer Academic Pub., Dordrecht, p. 359

McLean, I. S., Macintosh, B., Liu, T., Casement, L. S., Figer, D. F., Teplitz, H., Larson, S., Lacayanga, F., Silverstone, M. and Becklin, E. E. 1994 Proc. SPIE, Vol. 2198, Instrumentation in Astronomy VI, D. L. Crawford and E. R. Craine, eds., p. 457

Ueno, M. 1995 in IAU Symposium No. 167, New Developments in Array Technology and Applications, A. G. D. Philip, K. A. Janes and A. R. Upgren, eds, Kluwer Academic Pub., Dordrecht, p. 117

DISCUSSION

SZECSENYI-NAGY: We have seen some nice results on the IR photometry of intrinsically very bright stars and extragalactic objects. You also have shown us a deep image of the center of the Orion-nebula. As we know this region is extremely rich in red dwarf (dK/dM) stars. Do not you have any interesting and recent results on these absolutely faintest objects?

McLEAN: I have many other results which I could have shown including searches for very low mass stars and brown dwarfs. Others are doing similar work. I recommend to you the Proceedings of the UCLA conference of July, 1993 - Infrared Astronomy with Arrays: The Next Generation published by Kluwer.

SPYROMILIO: How confident are you that the big arrays will survive thermal cycling?

McLEAN: For InSb detectors thinned to about 10 μm one expects good resistance to thermal stresses because the material behaves like a "rubber sheet". For HgCdTe arrays on sapphire, the problem is greater. Rockwell and other companies have proprietary methods which will probably be sufficient - with care.

WATSON: What is the quantum efficiency of a Platinum Silicide detector?

McLEAN: Less than a few percent for commercially available devices.

WEAVER: Is anyone using InAs? Why not (since the QE seems high)?

McLEAN: Not to my knowledge. I think InSb technology is better developed.

CUBY: What about persistence effects with IR detectors?

McLEAN: Some HgCdTe arrays do show charge persistence effects. These can be reduced by resetting and flushing to some extent. Work is proceeding to eliminate the problem during construction.