McLeanゼミ

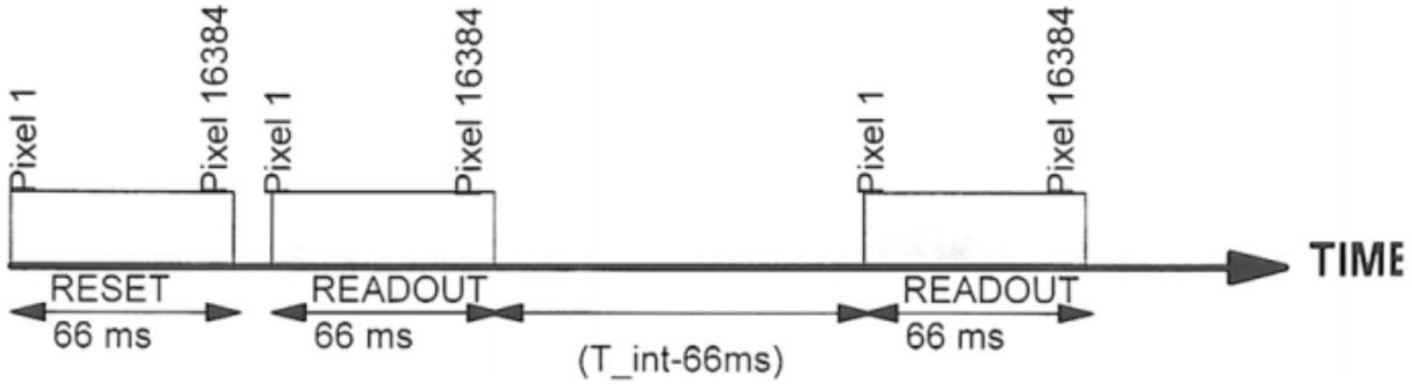
Sec.11.5.3-End of Sec.11

小島裕樹

Contents

11.5.3 Reset-read-read or Fowler sampling

- The best sampling scheme is as follows:
  1. reset the entire array pixel by pixel
  2. then immediately read out the entire array again but non-destructively, digitizing the signal in each pixel and saving this frame in memory
  3. after waiting the required integration time (T_{int}), non-destructively readout and digitize the whole frame again.
- This method is called the "reset-read-read" mode or the Fowler sampling mode and is less noisy than other methods.

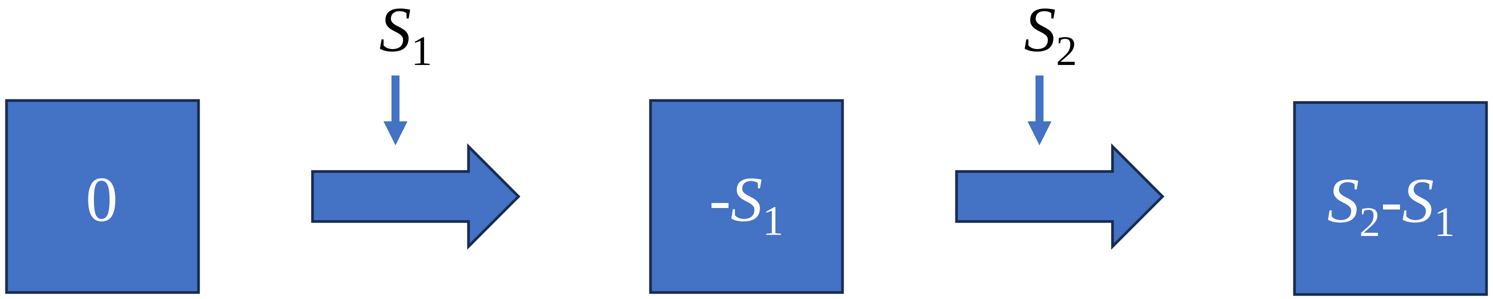


11.5.3 Reset-read-read or Fowler sampling

- The effective signal is the second read (S_2) minus the first read (S_1) :

$$S_2 - S_1 = [(T_{\mathrm{ro}} + T_{\mathrm{int}})\dot{N}_e + b + c] - [T_{\mathrm{ro}}\dot{N}_e + b + c] = T_{\mathrm{int}}\dot{N}_e$$

- The amplifier bias (b) and the unknown but correlated offset from the reset level (c) subtract out, and $\dot{N}_e$ represents a count rate [electrons/s].
- This differencing process is usually accomplished by storing the first read as a negative number and adding the second number to the stored value (rather than overwriting the value).



11.5.3 Reset-read-read or Fowler sampling

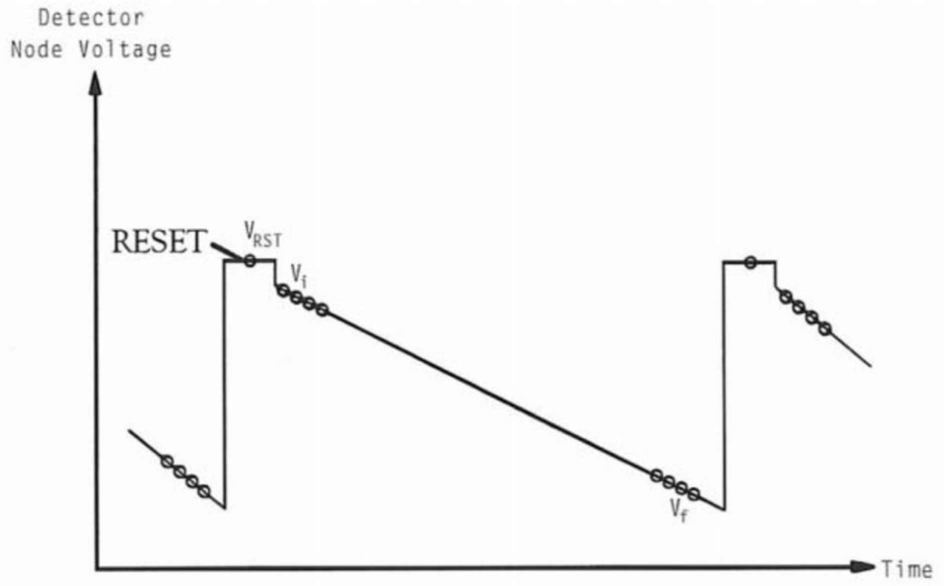
- Using the reset-read-read mode makes it harder to know when the array has saturated.
- For instance, suppose
  - the readout time is 66ms,
  - the pixel saturation level is 8,000DN,
  - the flux rate from a certain star is 60,000DN/s
  - the integration time (T_{int}) is 0.1s.
- Between reset and the first read each pixel integrates for 66ms, so the pixel with the star has a signal level of 3,960 DN when it is recorded.
- In the second read, 0.1s have elapsed and another 6,000 DN of charge should have accumulated giving a total of 9,960 DN.

11.5.3 Reset-read-read or Fowler sampling

- But the saturation level is 8,000 DN, and additional flux above this level cannot be recorded.
- Therefore, the actual value of the second readout will be 8,000 DN, and the difference ($S_2 – S_1$), which is all that is saved, will be 4,040 DN instead of 6,000 DN.
- The detector is hopelessly saturated, but the displayed counts do not indicate this.
- The way to check this is to use single-sampling mode and determine the true count rate on the star. A line plot across the star image will show a dip in the center.

11.5.3 Reset-read-read or Fowler sampling

- The reset-read-read process can be carried out multiple times to improve noise performance.
- For example, the initial (first) readout of the entire array following reset is repeated *m* times instead of once. ← Fowler-*m*
- The final full frame readout is also done *m* times.
- This is the usual case for narrow-band imaging and for near-IR spectroscopy where this technique is very effective in reducing noise.



11.5.3 Reset-read-read or Fowler sampling

- In Fowler-*m*, the difference of S_1 (the sum of the initial values) and S_2 (the sum of the final values) is,

$$S_2 - S_1 = mT_{\text{int}}\dot{N}_e$$

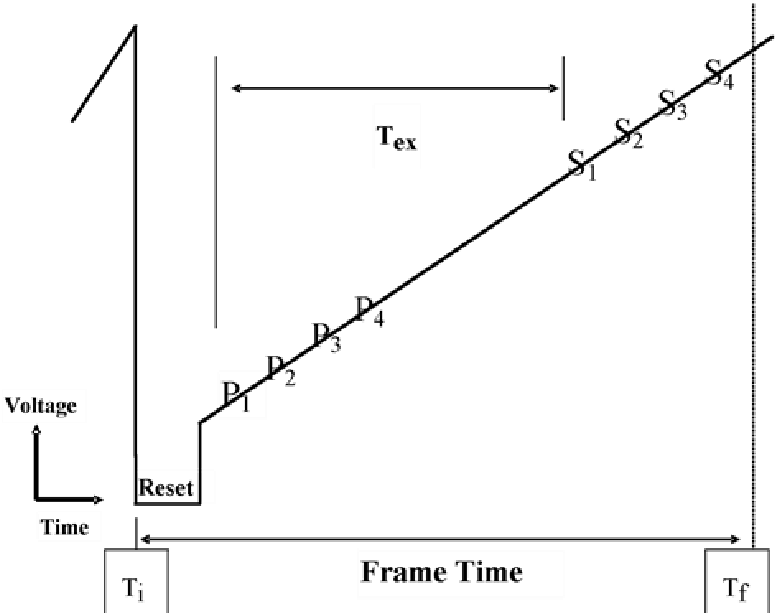
- By dividing this value by *m*, we get the desired integrated flux.
- The signal $S_2 - S_1$ is *m* times as large, but the readout noise is only $\sqrt{m}$ as large, so the effective readout noise in the final integrated flux is

$$R_{\text{eff}} = \frac{R \times \sqrt{m}}{m} = \frac{R}{\sqrt{m}}$$

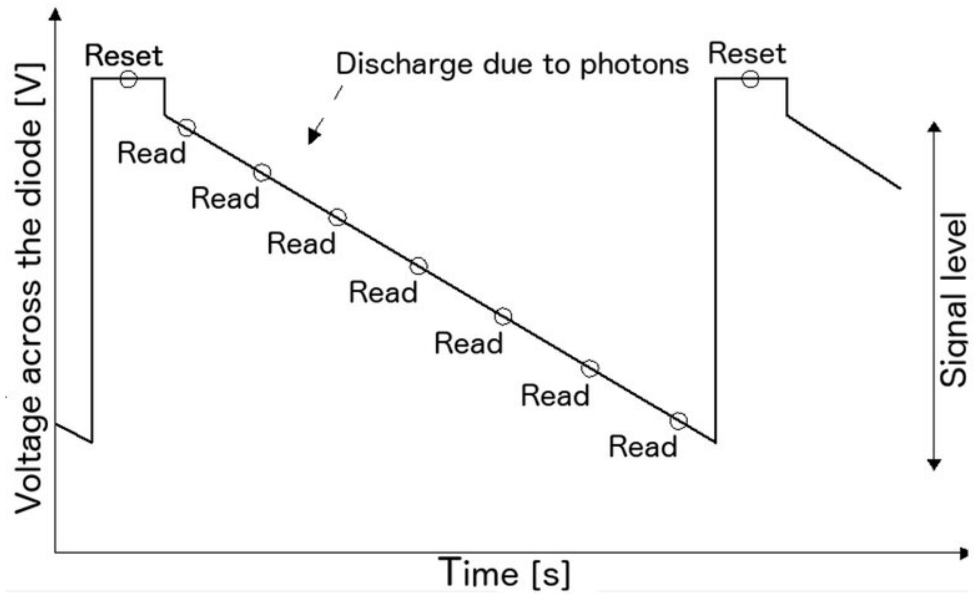
- For 16 reads ($m = 16$), the effective readout noise (R_{eff}) is only a quarter of the noise (R) obtained from Fowler-1. ($R_{\text{eff}} = R/4$)
- This technique has enabled NIR arrays to get down to below $5e^-$ rms noise despite their initially higher readout noise.

11.5.4 Sampling up the ramp (UTR)

- There is a sampling method that samples the signal many times at regular intervals throughout the exposure, not multiple times at the beginning and at the end.
- In this approach, the signal can be seen to "ramp" up, so it's called "sampling up the ramp (UTR)".



https://irsa.ipac.caltech.edu/data/SPITZER/docs/irac/iracinstrumenthandbook/8/



Dorn et al. (2023)

11.5.4 Sampling up the ramp (UTR)

- This approach is very useful in several situations:
  - ➢When some pixels may saturate before the end of the exposure time
  - ➢for space applications where the backgrounds are low, and cosmic-ray hits are frequent during long exposures
  - ➢for low-background AO applications and for low-background high-resolution spectroscopy
  - ➢for establishing steady-state thermal conditions in the detector which reduces drift

11.5.4 Sampling up the ramp (UTR)

- Garnett and Forrest (1993) showed that both multiple Fowler sampling and UTR sampling are superior to correlated double-sampling in readnoise-limited conditions.
- Both methods provide the expected $\sqrt{n}$ improvement, where n is the number of samples, unless or until 1/f noise dominates.
- Fowler sampling depends on duty cycle and is best when sampling the pedestal and signal levels each for 1/3 of the total observing time : a 2/3 duty cycle.
- Under these conditions Fowler sampling is approximately 6% inferior to UTR sampling.
- For background-limited performance the difficulty is that for any non-destructive multiple-sampling scheme, successive signal measurements are correlated in their noise.

11.6.1 General issues

- Every class of visible light instrument has its infrared counterpart, and building it is so challenging mainly because everything must be reduced to cryogenic (very low) temperatures.
- Many of the more robust IR optical materials (e.g., zinc sulfide, zinc selenide) don't transmit well in the visible, which hampers alignment and setup.
- Crystalline materials like calcium fluoride and barium fluoride which do transmit both optical and IR light are fragile and harder to work optically.

11.6.1 General issues

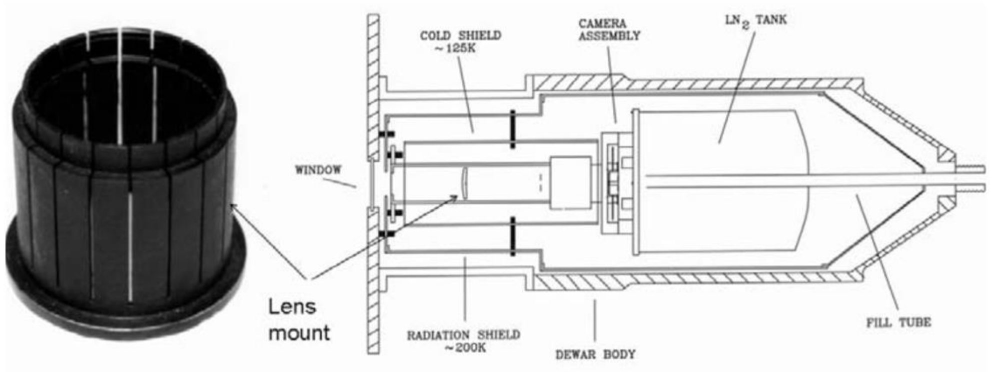
- To eliminate diffusely scattered light, you need to use blackened baffles.
- It requires care for several reasons:
  1. Anything truly black has almost 100% emissivity and will therefore be a strong infrared emitter unless very cold.
  2. Special infrared black paints such as Parsons black, Aeroglaze, and Nextel are required.
  3. If these paints are not applied carefully, they will eventually flake off due to cryogenic cycling.

11.6.1 General issues

- During cool-down of the instrument,
  - ➢parts not made from the same materials will shrink by different amounts due to dissimilar coefficients of expansion,
  - ➢lens holders could crush their optical components,
  - ➢optical separations will change,
  - ➢materials may experience stress.
- All these things must be calculated beforehand, and each component must be constructed in such a way as to achieve the correct dimensions after it is cold.

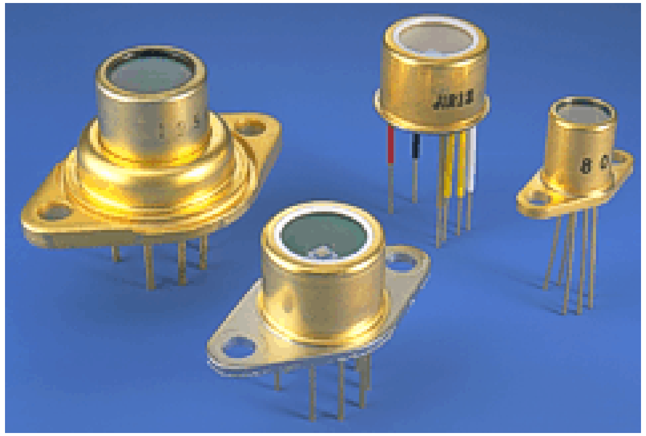
11.6.1 General issues

- One way to avoid damaging a lens is to use a holder which is springy. This can be achieved by cutting slits in the aluminum barrel.
- By matching the size of the cold stop to the size of the pupil image, unwanted off-axis rays from warm structure in the telescope are eliminated.
- The best cold stop is a “Lyot stop” which has a central disk (of metal) with four tiny supports designed to mask scattered light and thermal emission from the secondary mirror.



11.6.2 IR cameras

- Infrared cameras are now widespread.
- Short-wave mer-cad-tel (HgCdTe) with a cutoff at 2.5μm is very popular detector.
- LN_2-cooled cameras with 256 × 256 pixels or 1,024 × 1,024 pixels are easily operated with CCD controllers.



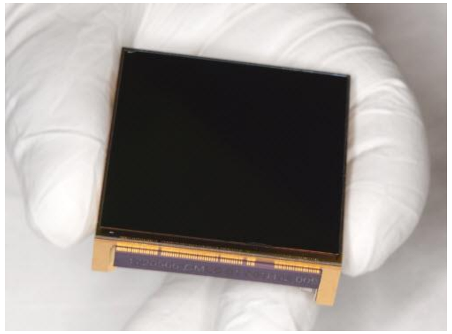
https://www.teledynejudson.com/products/photoconductive-mercury-cadmium-telluride-detectors

https://www.axiomoptics.com/products/irc800-ln2-cooled-mwir-scientific-camera/

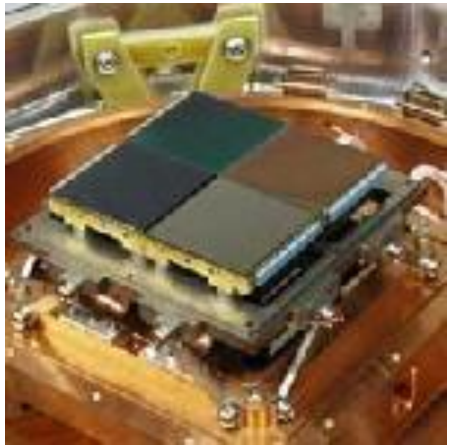
11.6.2 IR cameras

- Just like CCDs, larger format cameras use multiple arrays.
- One of the first of these was a mosaic of four 2,048 × 2,048 HgCdTe (H2-RG) arrays from Teledyne in the University of Hawaii's ULBCam used on their 2.2 m (88-inch) telescope on Mauna Kea.
- This 16Mpxl camera uses detectors being developed for the JWST near-infrared camera (NIRCam) .

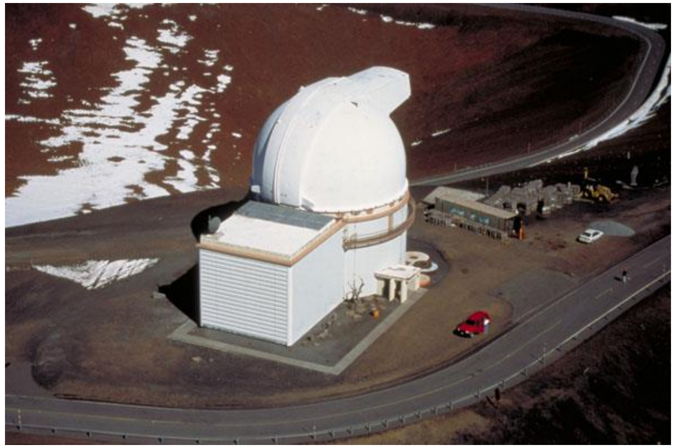
H2-RG



https://www.teledyneimaging.com/en/aerospace-and-defense/products/sensors-overview/infrared-hgcdte-mct/hawaii-2rg/



https://home.ifa.hawaii.edu/research/Detector_development.shtml

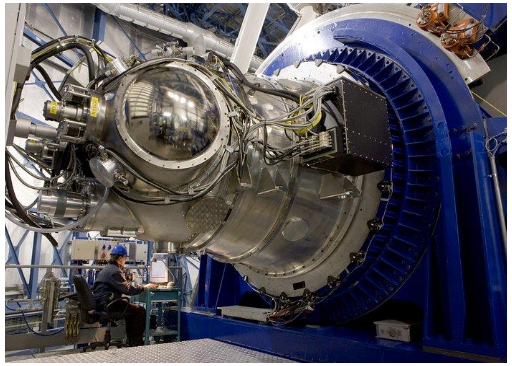


2.2m telescope (Credit:Richard J. Wainscoat)

NIRCam (Credit: Lockheed Martin)

11.6.2 IR cameras

- HAWK-I, which is a powerful new camera for the Nasmyth focus of UT4, one of the four 8 m VLTs, uses four 2K × 2K HgCdTe arrays to cover the 0.9μm-2.5μm, and has a FOV of 7.5’ × 7.5’ with 0.1” pixels.
- Wide Field Camera (WFCAM) for the 3.8 m UKIRT also has a mosaic of four 2K × 2K HgCdTe arrays and is used for UKIDSS surveys.
- At 2009, the largest IR camera was NEWFIRM, a New Extremely Wide-Field IR Mosaic for the NOAO 4m telescope on Kitt Peak (Arizona) which has four close-butted 2K × 2K InSb (Orion) arrays.

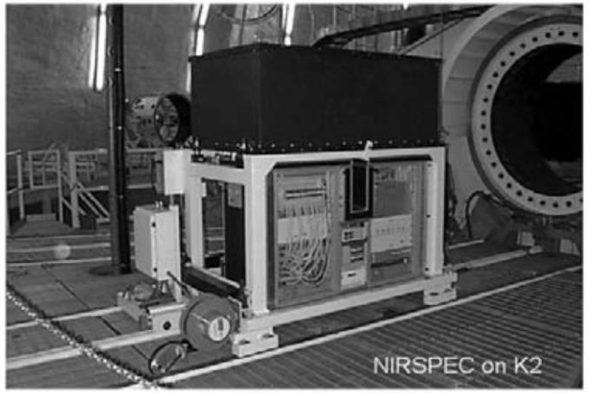

HAWK-I (Credit: ESO/H.H.Heyer)

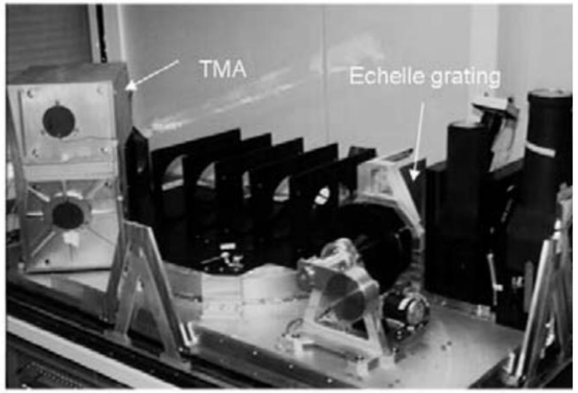

WFCAM (Credit: ROE/ATC)


NEWFIRM (Credit: CTIO/NOIRLab/NSF/AURA)

11.6.3 Infrared spectrometers

- Just like its optical counterpart, an infrared spectrometer relies on a diffraction grating, but unlike optical one, all components including the grating and the entrance must be cooled to cryogenic temperatures.
- NIRSPEC is a high-resolution, cross-dispersed infrared echelle spectrograph for the Keck Telescope with a $1,024 \times 1,024$ InSb array.
- Its optical system is laid out on a flat bench so care must be taken to prevent thermal gradients from the bench to the components.



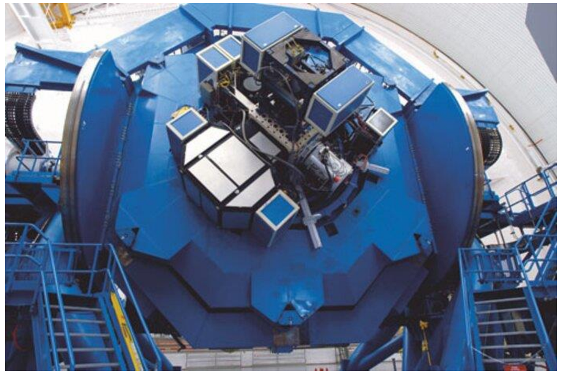


11.6.3 Infrared spectrometers

- There are two basic ways to achieve this: either by ensuring that the cross-sections of aluminum parts are large so that A/L is maximized, and/or attaching copper straps from the cold bench to the areas that need additional cooling.
- NIRSPEC is a near-infrared (1 μm-5 μm) spectrometer on a large telescope. Among MIR spectrometers are MICHELLE, a 7 μm-26 μm imager and spectrometer for the Gemini-N 8m telescope and T-ReCS (Thermal-Region Camera Spectrograph) on Gemini-S.

MICHELLE

(Credit: International Gemini Observatory/NOIRLab/NSF/AURA)

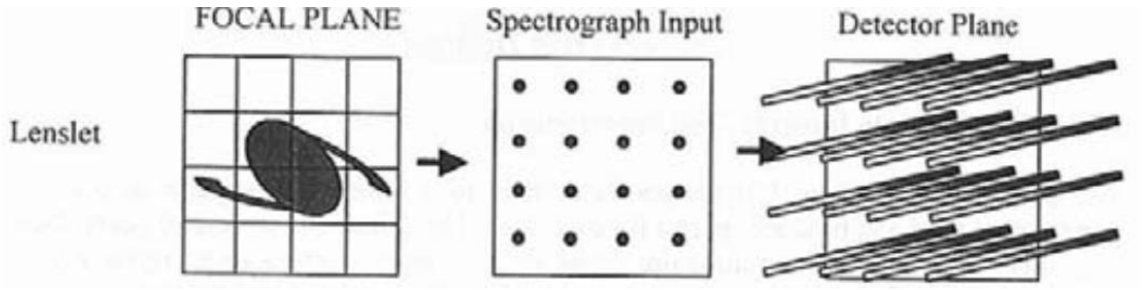


Gemini-S

(Credit: International Gemini Observatory/NOIRLab/NSF/AURA)

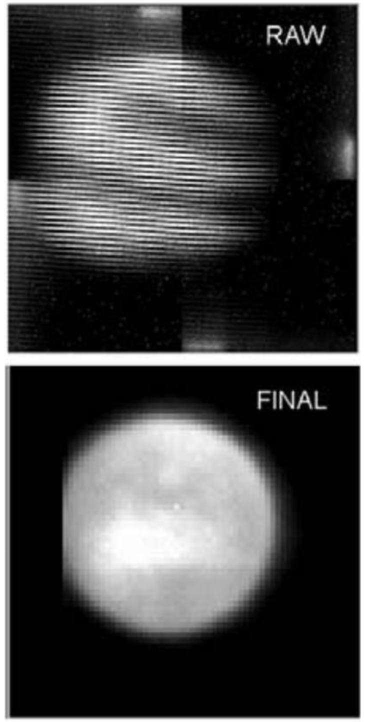
11.6.4 AO cameras and integral field spectroscopy

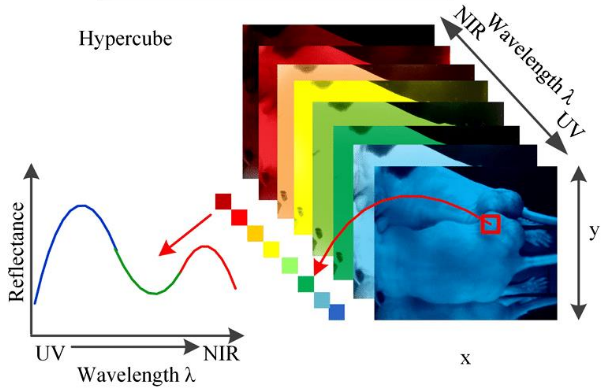
- Many NIR cameras have now been used with adaptive optics (AO) systems.
- Recently, many integral field techniques for the IR are also used.
- For example, OSIRIS, an instrument for the Keck telescope, is optimized for AO and employs an array of tiny lenses (called lenslets) for integral field spectroscopy.
- The input image is sliced up into hundreds of small spatial patches, then those images goes into the spectrometer.
- OSIRIS obtains both spatial and spectral information simultaneously.



11.6.4 AO cameras and integral field spectroscopy

- Images of Titan obtained with OSIRIS are on the right.
- On the top is the raw image on the detector. Although the vague outline of an extended object is apparent, it is hard to recognize it because this image is really composed of the spectra of all the tiny spatial locations.
- By cutting the datacube (x,y,λ) at a certain λ, then you "see" the image of the field at that wavelength.
- Some of the images in the stack will be badly affected by the presence of strong OH lines at that wavelength/position, so removing them and summing up the remaining images can form a deeper and less noisy image.

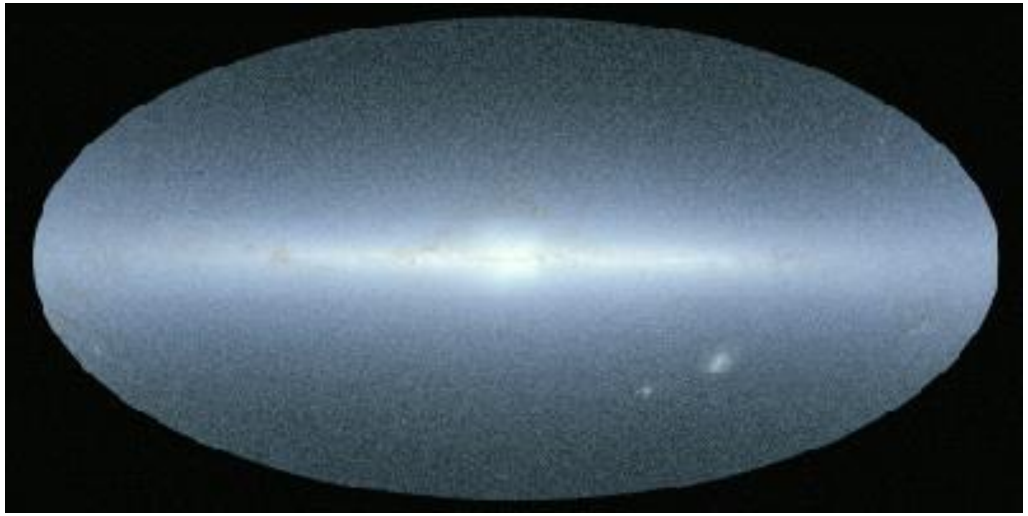




Vishvanathan et al. (2019)

11.7.1 Ground-based observing

- By 1994, near-infrared detector technology had made such huge advances that the only existing near-infrared sky survey, the TMSS (1969) no longer served as a useful basis for interpreting observations or selecting sources, so a new and deeper survey was needed.
- A new survey called the Two Micron All Sky Survey (2MASS) was conducted with 50,000 times the sensitivity of the original survey and with a resolution of 2arcsec.
- Two matching 1.3 m telescopes were placed in each hemisphere, the northern 2MASS facility began routine survey observations in 1997, and the southern instrument began in March 1998.



https://www.ipac.caltech.edu/2mass/releases/allsky/

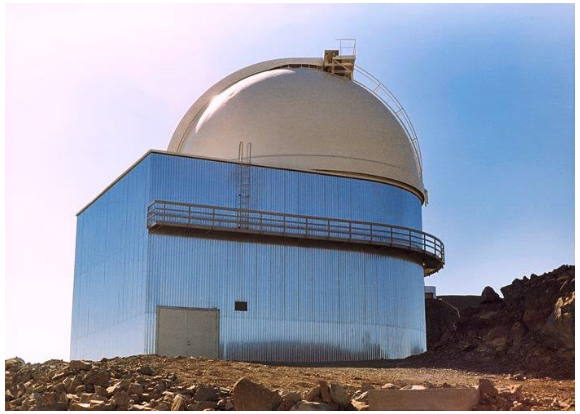
11.7.1 Ground-based observing

- The 2MASS cameras included three HgCdTe (2.5μm cutoff) infrared arrays with 256 × 256 pixels, one for each of the three bands J(1.25mm), H(1.65mm), and K_s (2.17mm).
- Other information
  - Imaging method: Time delay integration
  - Integration time: 7.8s
  - Mapping rate: 70 deg^2/band/night
  - Limiting magnitudes (S/N=10): J = 15.8, H = 15.1, K_s = 14.3
- Operations ended in 2001 and the 2MASS All-Sky Catalog was released in 2003, which includes
  - ~4 million 8' × 16' atlas images having about 4" spatial resolution in each band
  - accurate positions and fluxes for ~300 million stars and other unresolved objects
  - positions and total magnitudes for > 1 million galaxies and other nebulae

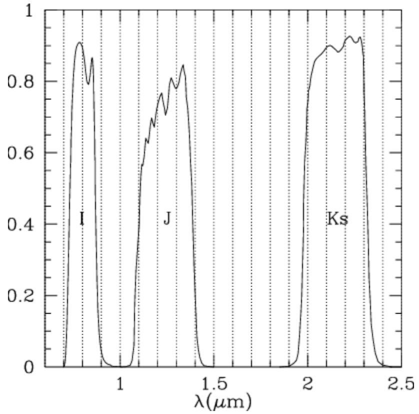
11.7.1 Ground-based observing

DENIS

- DENIS is a deep near-infrared survey of the southern sky in bands J (1.25 μm), K (2.16 μm) and I (0.82μm) simultaneously.
- This survey used a 1m telescope at LaSilla, Chile and had been conducted from 1996 to 2001.
- It provided 365 million sources, and the limiting magnitudes of the DENIS survey are: I= 18.5, J = 16.5 and K = 14.0, respectively.



The ESO 1-metre telescope on La Silla (Credit: ESO/Hochtief)

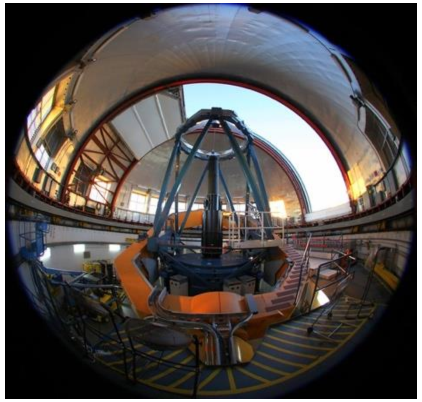


Fouqué et al. (1999)

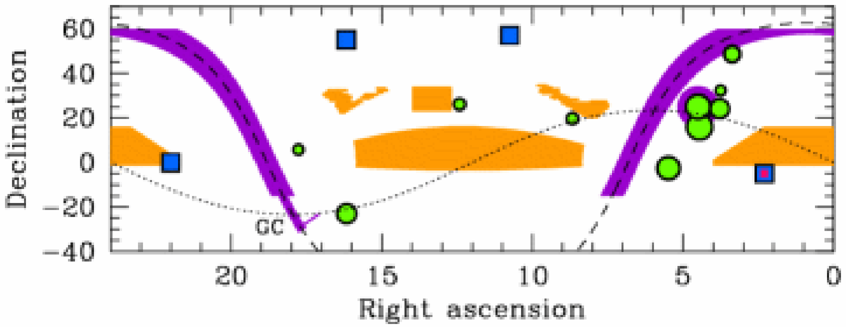
11.7.1 Ground-based observing

UKIDSS (UKIRT Infrared Deep Sky Survey)

- UKIDSS began in May 2005 and will survey 7,500 square degrees of the northern sky in JHK to K = 18.3 which depth is at least three magnitudes deeper than 2MASS.
- As of 2008, the survey instrument WFCAM had taken 30 times the amount of data taken in the entire 25-year history of the telescope (UKIRT) before its arrival.



UKIRT (Credit: Tom Kerr)



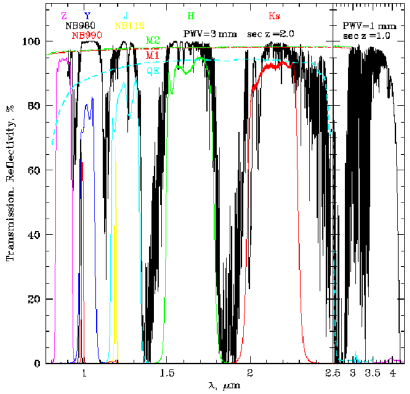
UKIDSS sky coverage (http://www.ukidss.org/surveys/surveys.html)

11.7.1 Ground-based observing

VISTA telescope (Credit: Martin Cullum)

VISTA

- A new telescope for a southern sky survey, VISTA was also being developed, which is a 4 m wide-field survey telescope
  - ➢equipped with a near-infrared camera (1.65-degree diameter field of view) containing 67 million pixels of mean size 0.34”
  - ➢observing at Z, Y, J, H, K and a narrow band filter at 1.18 micron.
- The telescope has an az-alt mount and quasi-Ritchey-Chretien optics with a fast f/1 primary mirror giving an f/3.25 focus to the instrument at the Cassegrain focus. Its camera contains
  - ➢16 HgCdTe VIRGO forming the largest IR mosaic thus far
  - ➢a wide-field corrector lens system (three Infrasil lenses)
  - ➢autoguider, active optics sensors …



https://www.eso.org/sci/facilities/paranal/decommissioned/vircam/inst.html

11.7.2 The Stratospheric Observatory for Infrared Astronomy

SOFIA (Stratospheric Observatory for Infrared Astronomy)

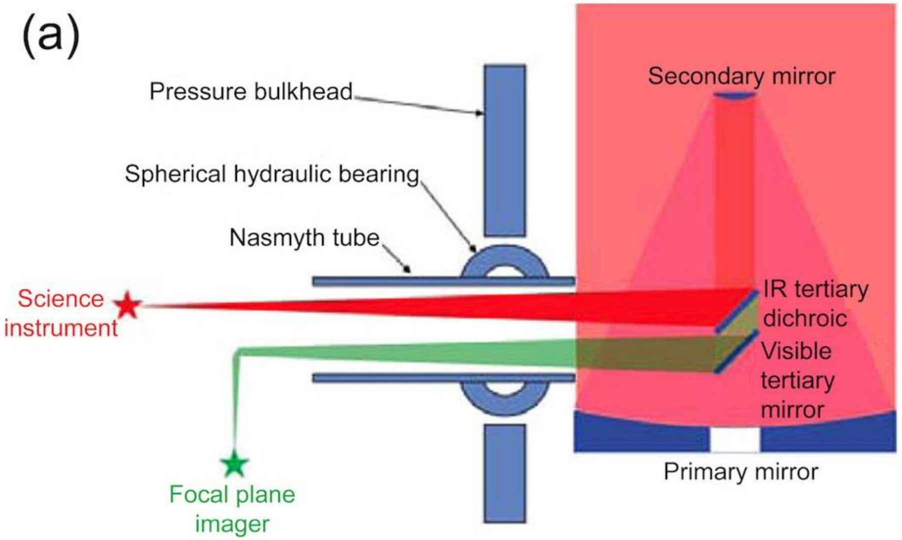
- SOFIA began preliminary operations in 2009 to advance airborne astronomy.
- SOFIA's telescope consists of a parabolic 2.7m primary mirror and a hyperbolic (chopping) secondary mirror in a bent Cassegrain configuration with two Nasmyth foci, a nominal IR focus, and an additional visible light focus for guiding.

https://www.csem.ch/en/news/sofia-the-airborne-observatory-in-search-of-extraterrestrial/

https://www.spie.org/news/6685-making-unique-ir-observations-with-an-airborne-25m-telescope#_=_

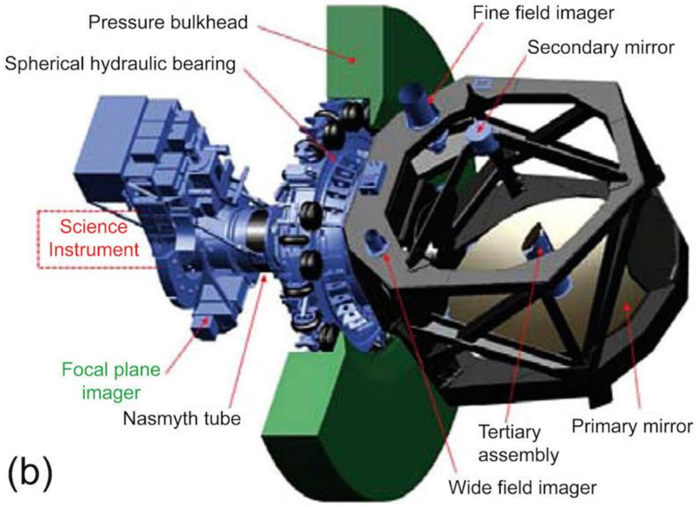
11.7.2 The Stratospheric Observatory for Infrared Astronomy

- A flat tertiary mirror reflects the IR beam into the infrared Nasmyth focus.
- If the fully reflecting tertiary is replaced with a dichroic mirror, the transmitted optical light is reflected by a second tertiary ~289 mm behind the dichroic and sent to the visible Nasmyth focus.
- There it is fed into the Focal Plane Imager (FPI), an optical guiding camera system.



https://www.spie.org/news/6685-making-unique-ir-observations-with-an-airborne-25m-telescope#_=_

11.7.2 The Stratospheric Observatory for Infrared Astronomy



https://www.spie.org/news/6685-making-unique-ir-observations-with-an-airborne-25m-telescope#B2

- Besides the FPI, there are two other imaging and guiding cameras available: the Wide Field Imager (WFI) and the Fine Field Imager (FFI).
- Both cameras are attached to the front ring of the telescope.
- Several interchangeable science instruments will be available for use on different flights, such as
  - ➢FORCAST (T. Herter, Cornell): Faint Object infraRed CAmera for the SOFIA Telescope (5μm-40μm)
  - ➢FIFI-LS (A. Poglitsch): Field Imaging Far-Infrared Line Spectrometer (42μm-210 mm)
  - ➢FLITECAM (I. McLean): First Light Infrared Test Experiment CAMera (1μm-5μm)

11.7.3 IR astronomy in space

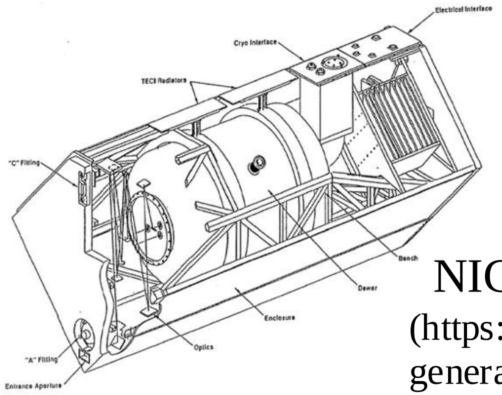
Hubble Space Telescope (HST) : NICMOS

HST (Credit: NASA)

- During the second Hubble servicing mission, the NICMOS (Near-Infrared Camera and Multi-Object Spectrograph) replaced the Faint Object Spectrograph (FOS) in 1997.
- NICMOS has three adjacent but not contiguous cameras.
- Initially the dewar's lifetime was expected to be 4.5 ± 0.5 years, but a thermal short after installation caused Camera 3 to be no longer parfocal with the other two cameras, and the lifetime was shortened.

> "the dewar was planned to warm up to about 57 K… The ice expansion caused by this temperature increase resulted in an additional dewar deformation,…The resulting heat flow caused the ice to warm up beyond expectations, to about 60 K, which in turn deformed the dewar more."

Barker, E., Pirzkal, N., et al. 2006, "NICMOS Instrument Handbook", Version 9.0, (Baltimore: STScI).



NICMOS (https://esahubble.org/about/general/instruments/nicmos/)

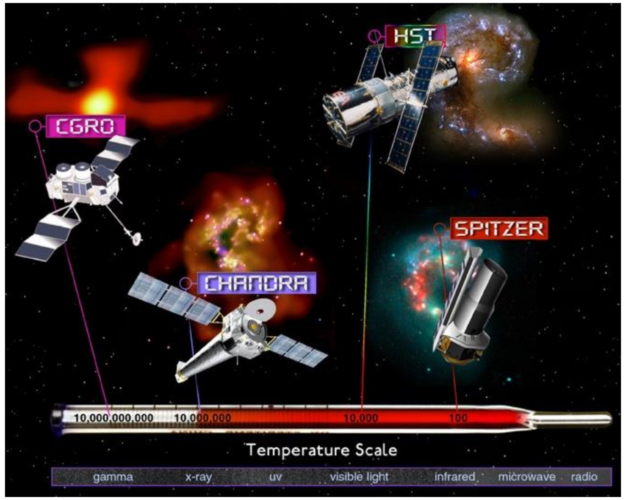
11.7.3 IR astronomy in space

- NICMOS was unavailable for science from January 1999 to March 2002 due to the cryogen depletion.
- During the third Hubble servicing mission a new NICMOS Cooling System (NCS) was connected which provided the cooling power to bring temperature down to 75K-86K.
- NICMOS employs three low-noise, high-QE, 256×256-pixel HgCdTe (2.5μm) arrays from Teledyne that were specially developed for this project.
- Because the HST primary mirror is maintained at a temperature of 20℃ to preserve its accurate shape, thermal background emission limits the use of Hubble in the infrared.

11.7.3 IR astronomy in space

Spitzer

- The “great observatory” counterpart to the Hubble Telescope for the infrared is NASA's Spitzer Space launched on August 25, 2003.
- Spitzer consists of
  - ➢a 0.85m light-weight f/12 beryllium mirror telescope cooled to about 5.5 K
  - ➢three cryogenically cooled science instruments covering the wavelength range from 3μm-180μm: IRAC, IRS, and MIPS.
- In addition to imaging and photometry from 3 mm to 180 mm, Spitzer also has a spectrometer for 5μm-40μm and a spectrophotometer for 50μm-100μm.



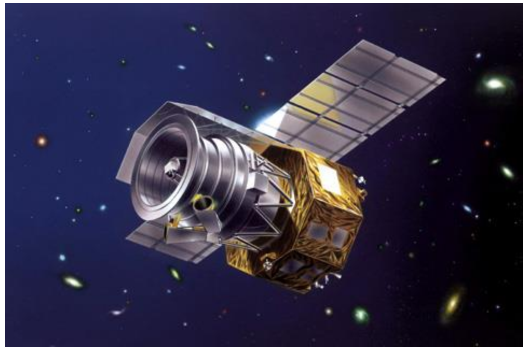
https://chandra.harvard.edu/blog/node/550

11.7.3 IR astronomy in space

Instruments on Spitzer are summarized briefly below:

- IRAC is a four-channel camera that provides images at 3.6, 4.5, 5.8, and 8μm over a 5.12’ × 5.12’ FOV. The two short-wavelength channels use InSb arrays and the long-wavelength channels use Si:As arrays.
- IRS has four separate modules:
  - a low-resolution (R), short-wavelength (λ) mode covering 5.3-14μm
  - a high-R, short-λ mode for 10-19.5μm
  - a low-R, long-λ mode for 14-40μm
  - a high-R, long-λ mode for 19-37μm
- MIPS has three detector arrays: one operating at 24μm, another for 70μm, and the rest for 160μm. MIPS is cooled by super fluid liquid helium to a temperature of about 1.5 K.

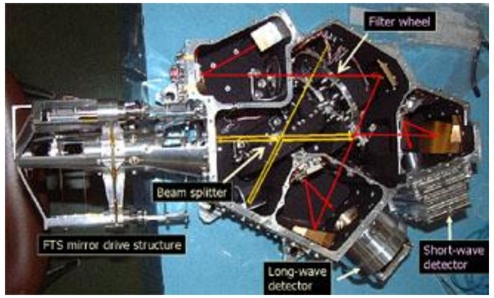
11.7.3 IR astronomy in space

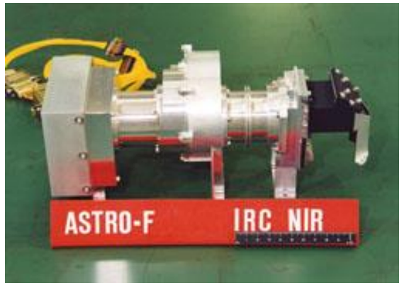


AKARI
https://global.jaxa.jp/projects/sas/astro_f/index.html

AKARI

- AKARI is an infrared astronomical satellite from the Japan Aerospace Exploration Agency (JAXA) launched in May 2006.
- AKARI has a 68.5cm telescope cooled to 6K, and observes in the wavelength range from 1.7μm to 180μm with two instruments:
  - ➢**FIS** (Far-Infrared Surveyor) covering four bands, 50-80μm, 60-110μm, 110-180μm and 140-180μm with two detectors
  - ➢**IRC** (InfraRed Camera) composed of three camera systems, NIR, MIR-S, and MIR-L covering 1.7-5.5μm, 5.8-14.1μm and 12.4-26.5μm respectively.





https://www.ir.isas.jaxa.jp/AKARI/about/instruments-j.html

11.7.3 IR astronomy in space

WISE
(Credit: NASA/JPL-Caltech)

WISE

- The next all-sky infrared survey was WISE, NASA's Wide-field Infrared Survey Explorer which was expected to launch in late 2009.
- WISE observed the entire sky in four bands: 3.3μm, 4.7μm, 12μm, and 23μm, known as W1, W2, W3, W4 respectively.
- W3 and W4 are like the IRAS bands, but WISE will be 500 $\times$ more sensitive than IRAS.
- Using a 40cm beryllium telescope and a scan mirror to stabilize the line of sight while the spacecraft continually scans the sky, WISE integrates for 11s during an exposure cycle and makes eight or more exposures at each position for over more than 99% of the sky.

11.7.3 IR astronomy in space

- The dramatic contrast between the Spitzer infrared image of M31 (Andromeda) and its well-known visual appearance is shown in the figure.
- In many cases the objects are optically invisible.
- Normal blue/green/red colors are used to “translate” the infrared images into a visual representation.
- All of the data reduction and data-handling techniques developed for CCDs are immediately applicable.
- Thus, the impact of infrared array technology has indeed revolutionized this field.

11.8 Summary

- Infrared array detectors are made from semiconductors with smaller bandgaps than silicon.
- Though similar to CCDs in terms of the conversion of photons to electrons, they don’t store charge or use the charge-coupling principle to read out the electronic image.
- Infrared arrays are constructed in two steps.
    1. a 2D grid of infrared detectors is formed on a IR-sensitive material
    2. a matching grid of field effect transistors is produced on a slab of silicon, together with additional circuits to “address” each pixel.
- These pieces are mated by “bump-bonding” them together with tiny columns of indium. Thus, the functions of IR detection and multiplexing the signals are separated.
- Infrared arrays are at or exceed the 1-megapixel level for the range 1-30μm, and arrays of ~1,000 elements are already possible in the far infrared.