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Infrared imaging and spectroscopy with small telescopes

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Abstract. This review discusses the issues involved in building infrared cameras and spectrographs for small telescopes. Ground-based infrared observations face more difficult observing conditions than equivalent visible light work, due to the absorption in the earth's atmosphere and emission from both the atmosphere and telescope itself. As a result, infrared instrumentation is generally an order of magnitude more expensive than the corresponding visible light instruments. On the other hand, some scientific questions can only be answered by infrared observations. Specifically for small telescopes, the most important niche are infrared monitoring observations of variable object, both with photometry and spectroscopy.
Key words: instrumentation – infrared

1. Introduction

Infrared Instrumentation is, in general, more expensive than equivalent optical instruments, and ground-based infrared observations are more difficult. There are, however, a number of astronomical problems that can only be addressed in the infrared and that make the extra effort worthwhile.

Interstellar dust in our Galaxy is concentrated in the Galactic plane and obscures the Galactic center and most distant star forming regions at visible wavelengths. Near infrared radiation, e.g., the K band around 2.2μm, suffers only 10% of the absorption at visible wavelengths. A more practical advantage of near-infrared wavelengths is that today's adaptive optics technology works well at these wavelengths on 8m-class telescopes, while optical wavelengths cannot be adaptive-optics corrected with the current level of this technology. An example of these first two advantages of infrared wavelengths is the work on the Galactic center by, e.g., Ghez et al. (2008). Intrinsically cool objects such as brown dwarfs and young gas-giant exoplanets can best be studied at near-infrared wavelenths as is demonstrated by the recent success in directly imaging large exoplanets, an example of which is the recent paper by Janson et al. (2013). Objects at cosmological distances have substantial redshifts that shift the rest-frame Lyman absorption by atomic hydrogen into the visible wavelength range. This leads to the phenomenon of "drop-out", where high-redshift objects are invisible in the optical bandpasses, but begin to be observable in the near-infrared. A recent example of this type of work is Labbé et al. (2013) on the spectral energy distribution of z≈8 galaxies.

The above examples of the advantages of infrared observations are certainly not "small telescope" science. When trying to identify suitable scientific projects for small telescopes with infrared capabilities, we must consider that the whole sky has already been mapped with the spatial resolution and sensitivity typical for small telescopes by the 2MASS project (Skrutskie et al., 2006), and by WISE (Wright et al. 2010) at longer wavelengths from space. Small infrared instruments are therefore best used to identify and study objects that vary, either photometrically or astrometrically. The time domain is still only poorly explored, even at visible wavelengths, and in the infrared, a huge amount of work remains to be done.

2. The Challenges of Infrared Observations

While the infrared wavelength region offer advantages for many important areas of astronomy, ground-based observations at these wavelengths face many challenges.

First, the atmosphere is not uniformly transparent in the infrared. Molecular absorption bands of H_2O and CO_2 divide the available wavelength range into distinct bands traditionally identified by letters: Y (1.05μm), J (1.25μm), H (1.65μm), K (2.2μm), L (3.5μm), M (4.5μm), N (10μm), and Q (20μm); details are given, e.g., in Tokunaga, (2000). The edges of these bands are limited by atmospheric absorption features and are therefore dependent on weather conditions, in particular on water vapor content.

Second, the night sky gets increasingly bright at longer wavelengths. The photometric B band ($\approx$.45μm) is largely unaffected by night sky emission lines, but starting in the V band ($\approx$.55μm), an increasing number on atomic and molecular night sky emission lines lead to a substantial photon flux from the sky that limits the sensitivity. The worst affected bandpass is the H band around 1.65μm where emission from individual lines of the OH radical forms an intense, and both temporally and spatially variable sky background. Starting at wavelengths above 2.0μm, thermal continuum emission begins to contribute, and becomes the dominant background flux at around 2.2μm. The L and M atmospheric windows are completely dominated by thermal emission. At wavelengths near 10μm, around the peak of the Planck function for ambient temperature objects, the very large thermal background makes ground-based imaging extremely difficult.

3. Infrared Instruments

3.1. Wavelength Coverage versus Price

From the practical standpoint of instrument design, we can identify several major breakpoints in the general trend towards more expensive and difficult instruments at longer wavelengths.

The first big step is the transition from silicon-based CCD or CMOS detectors below $\approx 1.0\mu$m to typical infrared detector materials like HgCdTe above this wavelength. Due to their more complicated hybrid design, more expensive detector material fabrication, and smaller commercial market, infrared detector arrays are nearly an order of magnitude more expensive than optical CCDs.

The second breakpoint is the wavelength limit of 1.8μm for imaging, the upper end of the H band. Cameras optimized for operation up to this wavelength can be built in the same basic way as an optical CCD camera, without the need for a cold pupil stop to reduce the thermal background. As long as either the detector is not sensitive beyond 1.8μm, or a suitable cold blocking filter is installed in front of the detector, the rest of the optical system, including the filters, can be at ambient temperature. From the standpoint of cost and complexity of the instrument, the need for wavelength coverage beyond 1.8μm and into the K-band should therefore be carefully evaluated.

In practice, the next price break occurs at 2.5μm. Cameras optimized up to that wavelength need a cold pupil stop for good background performance. They use the very common, high quality 2.5μm cutoff wavelength HgCdTe as detector material and can be cooled with LN_2 or with simple closed-cycle coolers down to about 80K. There are some very good achromatic material combinations available for this wavelength range that enable the design of relatively simple, high-quality re-imaging optics.

Beyond 2.5μm, the thermal background from the lower atmosphere and the telescope becomes the dominant problem. Compared to 2.5μm instruments, the costs get substantially higher due to lower operating temperature, higher light-tightness requirements, and more limited choice of optical materials.

Ground-based instruments working in the N window (10μm) and Q window (20μm) are in a class by themselves. They use doped-silicon photoconductor detector arrays optimized for high well capacity and extremely fast readout. The choice of optical materials becomes very limited, and most of these instruments therefore use purely reflective optics. Specifically for small telescopes, it should be noted that the point source sensitivity for background-limited and diffraction-limited imaging goes with the 4th power of telescope aperture, resulting in a huge disadvantage for small telescopes.

3.2. Design of Infrared Instruments

A common design problem in most infrared instruments is the control of thermal background. The goal is to block radiation from all directions, except for light passing through the telescope optics, or more precisely, the telescope pupil. This can be achieved by forming an image of this telescope pupil, in the simplest form by a lens placed close to the telescope focal plane (Fig. 1). This lens will form an image of the telescope pupil, usually the telescope primary mirror, but also image the central hole in the primary and the secondary support spiders. A cold aperture placed in this pupil image will block all radiation not coming through the telescope: thermal radiation from the mirror cells, from the telescope structure, from warm black baffles, and from the rest of the dome environment. To complete the design of a simple infrared camera, a lens system behind the cold stop re-images the original focal plane of the telescope onto the detector.

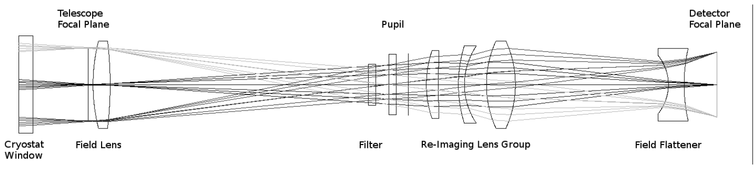

Figure 1. Optical Layout of the IRIS Camera (Hodapp et al. 2010). This design of an infrared camera for a small (80cm) telescope illustrates the basic design of most infrared cameras. The original focal plane of the telescope is inside a cryostat window. Very near that focal plane, a field lens is located and forms an image of the telescope pupil on a cold stop (the second plane parallel plate in this diagram). The filters are placed just in front of that pupil image. An achromatic triplet of lenses re-images the focal plane on the infrared detector, and a field flattener lens just in front of the detector corrects focal plane curvature.

A specific example of a very simple infrared camera for a small telescope is the IRIS infrared camera (Hodapp et al. 2010). This camera is a refurbished and modified version of the original QUIRC camera built in 1994 for the UH 2.2m telescope. At that time, it was the first camera to use a HAWAII-1 infrared detector array (Hodapp et al., 1996). The back half of the camera is taken up by a large reservoir for liquid nitrogen (LN_2) that cools the camera to 77K and provides in excess of 24h hold time. The detector array is thermally closely coupled to the liquid nitrogen tank, since it operates best at temperatures of 80K or below. In front of the detector are the re-imaging optics described above, and a filter wheel operated by a cryogenic stepper motor. The camera is enclosed in a vacuum vessel, as it is required for all cryogenic instruments. The IRIS camera is an example of the minimal configuration required for an infrared camera operating in the 1.0 - 2.5μm wavelength range.

3.3. Infrared Spectrographs

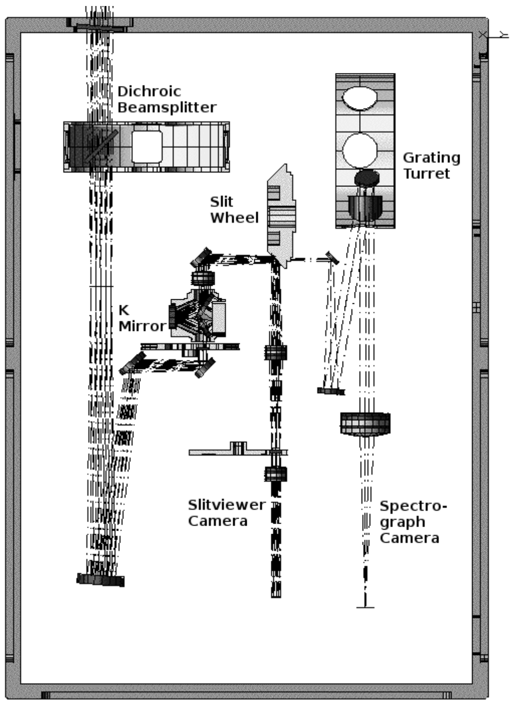

Figure 2. Optical Layout of the SPEX instrument, from the IRTF website (http://irtfweb.ifa.hawaii.edu/ spex/). Light coming from the telescope first passes through an optional dichroic beamsplitter to feed visible light to a guide camera. The transmitted infrared light reaches a collimator that forms a pupil image for thermal background rejection. A rotatable K-mirror serves to rotate the field so that the slit direction on the sky can be freely chosen. A lens system projects the object onto the reflective slit in the slit turret. This reflects the field surrounding the object into the infrared slit-viewing camera. Light from the target object passes through the slit into the spectrograph itself where it gets collimated, dispersed, and finally imaged onto the detector.

The design of an infrared camera can be extended to include limited spectroscopic capability by splitting the re-imaging optics described above into a collimator and separate camera. The resulting collimated beam can be used for dispersing gratings or grisms, or for polarization-splitting Wollaston prisms. While this gives the camera spectroscopic, or polarimetric capability, it usually also requires additional mechanisms for a focal plane wheel to selects slits or polarization masks, and usually separate dispersing and order-selection filter wheels. A major disadvantage of such simple spectrographs is the complete reliance on telescope tracking for slit positioning.

The solution to this problem is a separate slit-viewer camera that images the field reflected off the front surface of the slit. This can obviously be used for object acquisition and the documentation of the slit position. Since slits usually are about the width of the FWHM of the seeing, there is significant spill-over of object signal outside of the slit, and this can be used for guiding. The slit-viewing camera can be designed to be a capable general purpose infrared camera with multiple filters.

This basic design was first tried out with the KSPEC instrument in 1992 (Hodapp et al., 1994), and was then implemented in the IRTF facility spectrograph SPEX (Rayner et al. 2003). The SPEX has implemented another design feature for optimized sensitivity: Re-imaging foreoptics to block out-of-telescope thermal radiation before the near-diffraction-sized slit destroys the pupil image quality. For this particular instrument, a number of different option for the dispersion and cross-dispersion are provided, which give the instrument more flexible capabilities, but also increase complexity and cost.

For small telescopes with a corresponding limited budget for instrumentation, the best compromise may be a combination of a simple spectrograph with only one dispersion option, e.g., a cross-dispersed full coverage, moderate resolution spectrograph and a slit-viewing camera with a scientifically capable set of filters. In the interest of simplifying the design, and for operation out to 2.4μm, the cold-stop fore-optics may not be required. A final consideration is that when purchasing the infrared detector arrays for the instrument, it is often possible to purchase an engineering-grade array together with the full-quality science-grade detector array. It often turns out that the engineering-grade device is of sufficient quality for the slit-viewing camera.

4. Infrared Detector Arrays

Infrared detector arrays are at the core of any modern infrared instrument. In addition to the optical and technical issues discussed above, the high cost of these detectors drives the cost of infrared instrumentation an order of magnitude higher than similar instruments at visible wavelengths. In the past decade, two U.S. manufacturers have dominated the market for astronomical infrared detector arrays: Teledyne Imaging Systems, formerly Rockwell International, and Ratheon Vision Systems, formerly known as the Santa Barbara Research Center (SBRC).

The largest currently available detector arrays are in 2K$\times$2K format. Development of detectors in this format had been supported by the initial competitive procurement for the James Webb Space Telescope (JWST). While Raytheon went into that competition with InSb as detector material, HgCdTe has emerged as the best choice. For ground-based instruments with 2.5μm wavelength cutoff, it is the only choice. Both manufacturers are now offering 2K×2K devices with substrate-removed 2.5μm HgCdTe as detector material. The Ratheon product is the VIRGO detector array that, most notably, was used in the ESO VISTA camera (Bezawada et al., 2004), currently the largest infrared camera in the world. The Teledyne product is the HAWAII-2RG, short H2RG, where the R stands for "reference pixel", and the G stands for "guide window". These detector arrays have been used in a large number of ground-based instruments, and are, most notably, the chosen detector arrays for all the near-infrared JWST instruments (Blank et al. 2012b). Teledyne is offering an "application specific integrated circuit", the SIDECAR ASIC, as a readout electronics system for the H2RG detector arrays. This circuit, originally developed for JWST, provides a compact, almost turn-key solution for detector control.

The cost of infrared detector arrays are high, due to their more complex structure and difficult manufacturing compared to optical Si detectors. The main cost driver is the manufacture of the detector material. For HgCdTe, the crystallographically correct way is to epitaxially grow the HgCdTe on a matching crystal lattice, which is CdZnTe. Unfortunately, there is only one manufacturer for large format CdZnTe substrates in the world, and prices are high. The process of growing the detector material on these substrates requires very precise process control and is the main yield-limiting process in the production of infrared detector arrays.

A Teledyne development project run by D. Hall from the University of Hawaii is developing the 4K×4K H4RG detector array (Blank et al. 2012). After many refinements in the process, the first science-grade devices are now being fabricated. This huge detector array will be very expensive, even though the cost per pixel has come down by a factor of two compared to the previous generation of devices. The cost of one of these devices is comparable to the cost of a 1m-class telescope, so they may not be affordable for smaller observatories.

A new company in the market for astronomical infrared arrays is SELEX, a U.K. company. They used to mostly serve the defense and security market, but have now developed a very interesting small avalanche photodiode infrared detector array capable of photon-counting performance, the SAPHIRA array. The first test results on these devices at ESO have been reported by Finger et al. (2012). While this is a small array may be primarily of interest for wavefront sensing and very fast photometry, SELEX also have ongoing development programs for arrays of 1920×2080 and 2K×2K under contract from ESA. SELEX use a metal-organic-vapor epitaxy process for detector material growth and can, apparently, produce high quality detectors at quite reasonable cost.

In general, the performance to today's infrared detector arrays with 2.5μm HgCdTe is entirely adequate for ground-based imaging and low- to medium-resolution spectroscopy. The non-destructive read process allows to reduce the effective read-noise to well below 10 e rms by multi-sampling. Dark currents at operating temperatures below 80K are generally below natural or instrumental background and scattered light levels. Quantum efficiency is generally high and reasonably uniform over the wavelength range of interest. A remaining issue is the nuisance of image persistence, i.e., the fact that previously strongly exposed pixels leak current in subsequent exposures, leading possibly to mistaken identification of variable sources, or at least to cosmetic problems in the images.

5. Conclusions

The infrared wavelength range presents additional challenges when compared to visible wavelengths. Infrared instruments are more complex, and infrared detectors are more costly than equivalent visible light instruments. With increased competition in the astronomical detector market and improvements in their manufacture, there is the potential for slowly decreasing prices for these detectors. However, telescopes suitable for infrared observations and infrared instruments are about an order of magnitude more expensive than small telescopes operating with visible light instruments. On the other hand, time-domain studies on many classes of objects accessible only at infrared wavelengths remain largely unexplored and could become fruitful research field for relatively small telescopes.

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