ONCE YOU START ASKING

Telescopes 1
The MODS Instrument

INSIGHTS, STORIES AND EXPERIENCES

from ten years of reporting on science and engineering

MARKUS VOELTER

Overview. On our trip from Los Angeles airport to SOFIA's Palmdale base we visited the 100-inch Hooker telescope on Mount Wilson. It was the largest optical telescope for its time—first light was 1917. Edwin Hubble used it to make the observations with which he showed that the universe is expanding. It is a Newtonian reflector with observing stations at the Cassegrain focus behind the main mirror/lens and at right angles to the primary focus. It actually has eyepieces at these two locations, with a neat little wooden chair on a raised platform for the Newtonian focus (I wonder how many people fell off the chair and down from the platform while they were observing in the dark of night). This is a historic telescope, and of course I was aware that modern telescopes don't use eyepieces: imaging and spectrographic instruments are used instead. A few days later I would see one of those: the 600-kg FIFI-LS mounted on the SOFIA telescope, during my flights. However, when I visited the LBT, the size and complexity of the instruments was something else.

LBT hosts a range of instruments, most of which are permanently installed; they receive their input by redirection of the light path, as I have explained. The two Large Binocular Cameras are installed in the prime focus of each telescope in place of the secondary mirror. LUCI 1 and 2 are infrared instruments that support imaging and spectroscopy, installed on the gallery between the two mirrors. PEPSI is another spectrograph that can also be used to determine the polarization of the received light; this is in turn an indicator of the presence and orientation of magnetic fields around the target. PEPSI is installed away from the telescope in a pressure- and temperature-stabilized room, receiving its light via 45-meter-long glass fibers. In 2019 two new instruments called SHARK will be installed. These will be especially suitable for detecting exoplanets—one of the main missions of the LBT—because of their use of coronagraphy, which blocks out the light from the central star and greatly improves the contrast in the region around it. MODS is a multi-object optical spectrograph, and LINC NIRVANA is a near-infrared interferometer. We'll look at these two in more detail.

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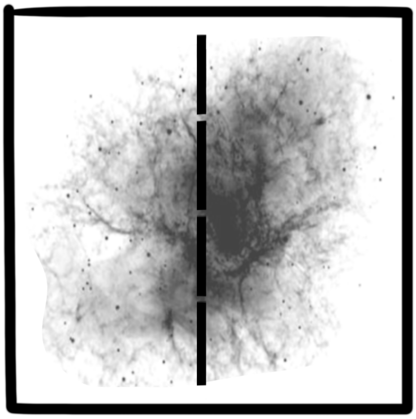
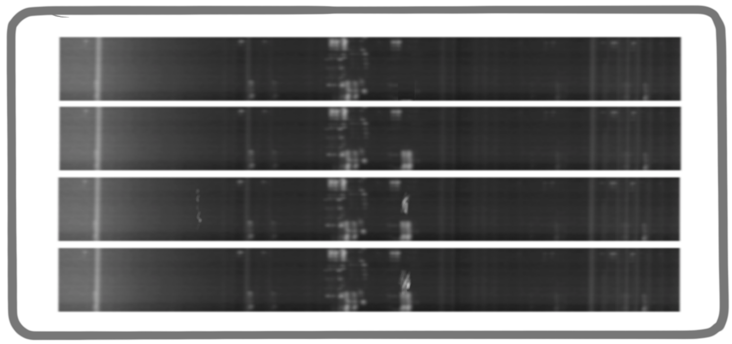
MODS. MODS is a spectrograph; it analyzes the wavelength content of the received light, as we saw in SOFIA. For this task, the resolution of the telescope is not that important; what counts is the light-gathering power, because this reduces integration times. This is why, when used for MODS, the two mirrors are operated in non-interferometric mode. LBT has two separate MODS instruments, mounted on the Gregorian focus behind each primary mirror (position 5 in the illustration a few pages back). MODS is several meters long and wide, and is roughly the size and shape of the Mercury spacecraft, but at 3,000 kg is twice as heavy, to provide the rigidity necessary for the precise optics inside. The large size is to ensure a light path that is as straight as possible, thus requiring fewer optical elements. This, in turn, is important for violet and ultraviolet radiation, which is absorbed by optical elements. MODS' mount is derotated, which means that the orientation of the image (or spectrum) remains stable as the telescope rotates to follow the night sky. As you would expect, the detectors inside the instrument are cooled to keep thermal noise low, in the case of MODS to "only" around 170 Kelvin, which can be achieved with liquid nitrogen. The coolant is brought up to the telescope once a week with a pickup truck. MODS is another example of we-can't-built-it-precisely-enough-so-let's-not-even-try: the alignment of the instrument with the telescope will change slightly as the telescope moves (and changes the orientation of the instrument). This is why MODS has a little infrared laser beam and a separate detector that actively controls the alignment of the optics.

MODS is of course an abbreviation—it's short for Multi-Object Double Spectrograph. The "spectrograph" is obvious, so let's understand the other words. "Double" refers to the fact that inside each instrument there are two separate detectors, one for blue light (300 to 570 nm) and one for red light (570 to 1000 nm). In each channel the optical elements such as mirrors, dispersers, cameras and CCD detectors are optimized for the respective blue or red wavelength region.

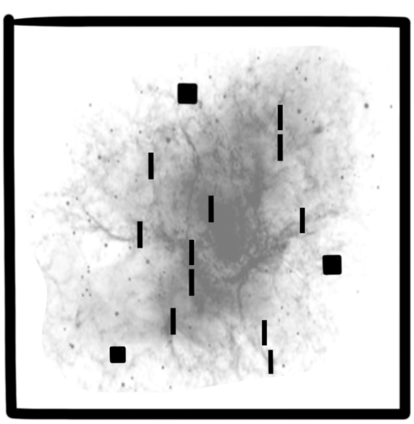
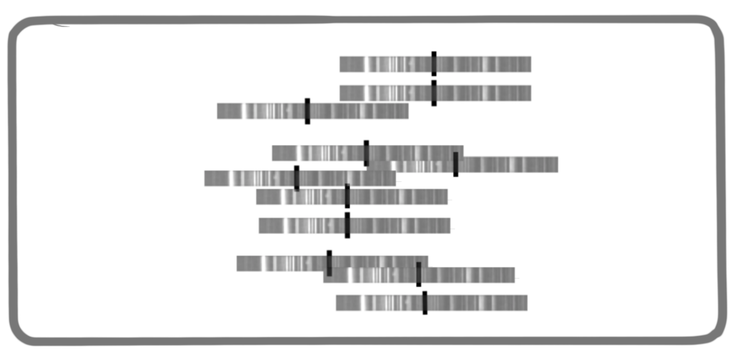
"Multiple Object" takes a little more explanation. First, since MODS is an instrument on an optical telescope, it observes both in the visible range and the adjacent near infrared and ultraviolet bands. For these bands you don't need fancy pressurized crystals as they do for the (further) infrared light in FIFI-LS; the spectrum can be recorded by a CCD chip which, as we know from digital cameras, can be packed very densely. MODS has an 8192 x 3088 chip, about 25 megapixels. The reason why it is wide instead of square (even though the beam received from the telescope is circular) is because the spectra are spread laterally across the chip. Let's call this the x axis, and the vertical, shorter side we'll call the y axis.

We know from SOFIA that one way of producing a spectrum is to let the light fall onto an optical grating, which then reflects each of the component wavelengths at a characteristic angle. This wavelength-separated light falls onto the respective x-location of the CCD, and the brightness recorded there then corresponds to the energy content at the respective wavelength; the brighter, the more energy. Importantly, if one let the whole image fall onto a grating every point would produce a spectrum, and these would overlap, resulting in a useless mess. Therefore, to create useful spectra, the area onto which the spectrum is projected must be kept dark (in the sense that no image light strikes it, only the light dispersed by the grating). This is why MODS can insert masks into the light path: they make sure that only a thin slit of light reaches the grating and the rest of the CCD is kept dark, allowing the spectrum created by the grating to be captured by the CCD.

This particular kind of grating-created spectrum expects the slits to be in the middle of the x axis of the mask; the spectrum is then spread out over approximately 6,000 pixels along the x axis. The approach can be used to capture the spectrum of a single target object or, by arranging several slits vertically, an object's extent along the y axis can be resolved into several spectra arranged beneath each other on the CCD. MODS has a set of predefined masks with five slits arranged vertically at x center. Different slit widths are available to take care of different intensities of the target object.

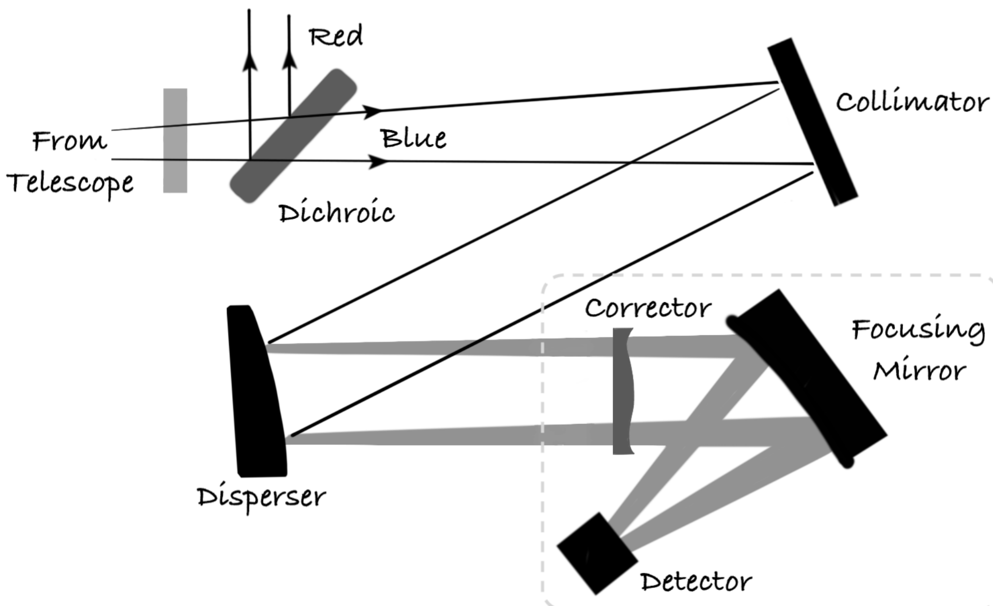
 

However, as the “MO” in MODS suggests, the instrument can also capture the spectra of multiple objects in the field of view, ideally even when they are not aligned in a straight line down the middle of the image. For this use case, scientists can use custom masks with mini slits all over the square region of the image. Here, the spectrum is not created with a grating, but with a prism; this produces a spectrum that has lower resolution, resulting in a spread in x direction of only around 600 pixels. This allows dozens of mini slits to be placed on the surface of the mask as long as they are either at different locations on the y axis, or far enough apart in x direction for the 600-pixel-wide spectra not to overlap. The masks also contain a couple of square holes that help with alignment of the observation.

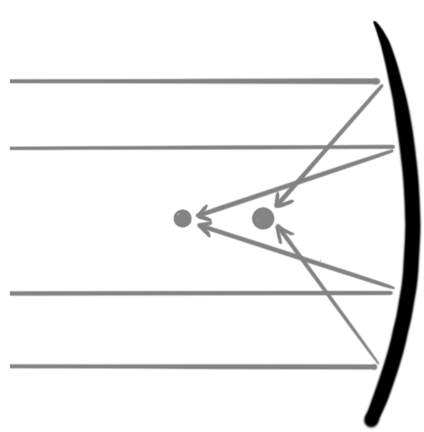
 

A software tool helps with the design of the masks; users can put an image of the target region as the background and then "draw" the slits onto interesting regions of the image. The tool also helps to ensure that the resulting spectra do not overlap. Masks are made of thin black sheet metal cut by a precision laser cutter, done in a clean lab at the University Research Instrument Center on the University of Arizona campus in Tucson. Once at the telescope the masks are inserted into a jukebox mounted on the side of the instrument; this allows the observers to exchange masks automatically during an observation. Switching from the grating to the prism happens by rotating a roughly one-meter diameter selector turret, which also contains a flat mirror that can be used for a (non-spectrum) imaging mode that is particularly useful during alignment of the telescope.

The diagram below shows the overall optical path of MODS, illustrated for the blue band; the red band has a similar structure. The two bands are separated at the entry of the instrument using a dichroic mirror, which reflects light of a particular wavelength (range) and lets other wavelengths pass through. In each of the two channels the light then strikes a collimating mirror that turns the diverging light rays from the telescope's focal plane into a parallel beam about 420 mm wide. This then hits the disperser (the prism or the grating) that spreads the light.



The remainder of the optics (enclosed in the dotted box above) is a Maksutov–Schmidt camera, a design similar to the Schmidt–Cassegrain telescope that is popular with amateur astronomers. It has a concave, spherical main mirror that focuses the image onto the detector. Such mirrors have various aberrations, the most important being the spherical aberration: a spherical mirror does not focus all incoming light onto the same point. The further out from the optical axis, the closer the focus is. This means that if you insert a sensor at the focus, only a part of the overall field of view will be "sharp".



The corrector lens in the MODS camera, and the Schmidt plate in Schmidt–Cassegrain telescopes, compensate for this aberration. The final component is the CCD detector that sits at the focus of the camera, which is located off axis to ensure that the detector does not create a shadow on the mirror.

A mirror with a parabolic shape does not suffer from spherical aberration. You might ask, therefore, why they didn't use a parabolic mirror. This is because it exhibits another distortion, called "coma". We'll discuss this later in this chapter, but for now let's just say that coma is not necessarily easier to correct than the spherical aberration of spherical mirrors.

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