Astronomical observations: a guide for allied researchers

P. Barmby
Department of Physics & Astronomy
University of Western Ontario
London, Canada N6A 3K7

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Abstract

Observational astrophysics uses sophisticated technology to collect and measure electromagnetic and other radiation from beyond the Earth. Modern observatories produce large, complex datasets and extracting the maximum possible information from them requires the expertise of specialists in many fields beyond physics and astronomy, from civil engineers to statisticians and software engineers. This article introduces the essentials of professional astronomical observations to colleagues in allied fields, to provide context and relevant background for both facility construction and data analysis. It covers the path of electromagnetic radiation through telescopes, optics, detectors, and instruments, its transformation through processing into measurements and information, and the use of that information to improve our understanding of the physics of the cosmos and its history.

1 What do astronomers do?

Everyone knows that astronomers study the sky. But what sorts of measurements do they make, and how do these translate into data that can be analyzed to understand the universe? This article introduces astronomical observations to colleagues in related fields (e.g., engineering, statistics, computer science) who are assumed to be familiar with quantitative measurements and computing but not necessarily with astronomy itself.[1] Specialized terms which may be unfamiliar to the reader are italicized on first use. The references in this article are to a mix of technical papers and less-technical descriptive works. A shorter introduction to astronomical observations and associated statistical considerations is given by [20]. Comprehensive technical introductions to astronomical observations are found in several recent textbooks [9, 28, 32].

This article focuses on astronomical observations of *electromagnetic radiation*. Electromagnetic radiation is thought of in two complementary ways: as waves characterized by *wavelength* λ or frequency ν, or particles called *photons*, characterized by their energy (see Fig. 1). Radiation with small wavelengths consists of photons with large energies, and vice versa. Different types of electromagnetic radiation are given different names, including "X–ray," "ultraviolet," "infrared," but these are fundamentally the same physical phenomenon and the same theoretical understanding applies to all of them. On Earth, radio-wavelength radiation is often used to transmit encoded data, sometimes audio information—but radio waves are electromagnetic radiation, not sound waves.

[1] In present-day practice there is no distinction between 'astronomy and 'astrophysics'; the two are used interchangeably.

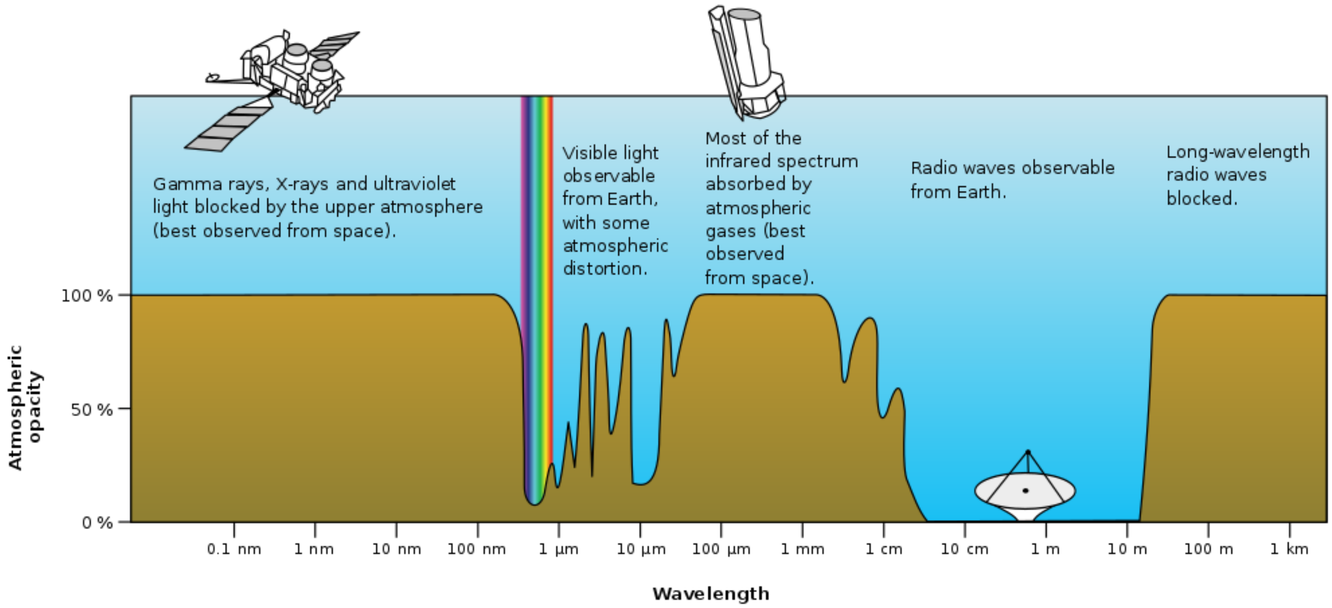

Figure 1: The electromagnetic spectrum and its transmittance through Earth's atmosphere. Credit: NASA via Wikimedia Commons.

The objects that astronomers study, including stars, planets, nebulae, and galaxies, produce radiation in different ways depending on their physical properties (e.g. composition, density, temperature) and environments. This means that they will emit different amounts of radiation at different wavelengths. This radiation is modified on its way to Earth by processes such as absorption and scattering in the intervening interstellar or intergalactic material. For objects well outside our own Milky Way galaxy, radiation is also *redshifted* — that is, shifted to larger wavelengths or smaller frequences — by the expansion of the universe. Measuring the radiation from astronomical objects and interpreting those measurements is what observational astrophysicists do. Developing physical models to predict and explain the radiation detected from astrophysical objects is the domain of theoretical astrophysicists. For objects which radiate in all directions (which most but not all astrophysical objects do), the received intensity decreases with the square of the distance from the source. Only a tiny fraction of the radiation from an astrophysical object is aimed in our direction, and that fraction is smaller for more distant objects. Astronomical observers are very often working in the low signal-to-noise regime, at the very edge of detectability.

Astronomical observations are nearly always *passive*—we have no ability to directly manipulate or experiment with the objects of interest. In most cases we rely radiation on emitted from these objects reaching our telescopes. This is in contrast to *active* remote sensing, such as sonar or radar, where radiation is transmitted to the object and scattered or reflected back for detection. Active sensing beyond Earth is confined to radar studies of objects within the solar system: objects beyond the solar system are simply too far away for a signal to return in a detectable way in a reasonable period of time! Direct physical contact with the object of interest is restricted to a few situations within the solar system (e.g., sample returns from the surfaces of solid bodies or particle collection from the solar wind). Rather than "observational astronomy," this kind of study would usually be called "planetary science" or "space physics," respectively.

Astrophysics is unique among sciences in the range of size scales involved. We explore relationships between the largest and smallest scales of the universe, relating atoms to galaxies. Both the technology used to make our observations, and the physics used to interpret them, span a similarly broad range. Observational astrophysicists need familiarity with a variety of experimental, statistical and computational techniques and technologies.

2 Telescopes and optics

The fundamental measurement that an astronomer makes is the amount of radiation from the sky, as a function of direction, time, wavelength or frequency, and polarization.[2] The long history of astronomical measurements [19] began with observations made by the human eye and brain, later aided by architectural constructs like Stonehenge or devices like the sextant. The invention and adoption of the telescope transformed astronomy, and to many people, astronomy *is* telescopes and vice versa. Telescopes are only the beginning, however!

In non-astronomical situations (for example, by bird watchers or pirate captains), telescopes are used to magnify images of distant objects so that they can be identified. The two main uses of astronomical telescopes are different: (1) collecting as much radiation from the sky as possible (acting as a "light bucket") so that faint objects can be detected, and (2) precisely determining the location in the sky from which radiation is emanating. Once radiation is collected by a telescope, it is detected via human eye, photographic plate, or electronic detector. Human eyes are not the detector of choice for professional astronomical telescopes: electronic detectors are much more efficient and easily-calibrated collectors of radiation. They can be made to respond to radiation at wavelengths other than the visible light we see with our eyes or the infrared radiation we feel as heat on our skin.

The idea of a telescope as a "light bucket" helps to explain why astronomers like larger telescopes. In a rainstorm, a bucket with a larger top opening will collect more rain. Similarly, a telescope's effectiveness at collecting radiation from the sky depends on its *cross-sectional area*, which depends on the square of the diameter of its main mirror or lens, D^2. Over the same period of time, a larger telescope will collect more radiation than a smaller telescope. Because astronomical objects are far away, only a small amount of their radiation reaches us—and getting more light from an object usually means that measurements have lower uncertainties.

Larger telescopes are also important for the second purpose of telescopes described above: localizing the direction of emission. This is done by focusing the radiation, which requires changing its direction. Focusing can be done in one of two ways: *refraction* or *reflection*. Refraction is familiar from other optical instruments such as eyeglasses and microscopes, and involves bending of light through a lens material (usually glass). Because it's difficult to make very large lenses, most modern large astronomical telescopes bend light using reflection by curved (usually parabolic) mirrors. These mirrors can be made of materials similar to familiar everyday mirrors—silver- or aluminum-coated glass—or rather different, such as the beryllium mirrors on the James Webb Space Telescope (JWST)[3] or the wire surfaces of a radio telescope.

Some specialized types of telescopes do not directly focus the incoming radiation. The very high energies of gamma rays mean that it's very difficult to change their direction. In current gamma-ray astronomy, localization of gamma ray photons is done via other techniques, including the use of coded-aperture masks, which cast a gamma-ray shadow onto a detector, or tracking the shower of visible-light Cerenkov radiation that results when gamma rays pass through the Earth's

[2] While polarization can be quite important for understanding certain types of astrophysical objects, it's quite difficult to measure and mathematically complicated so won't be discussed further here.

[3] Astronomers enjoy acronyms. See https://www.cfa.harvard.edu/~gpetitpas/Links/Astroacro.html.

atmosphere [8, 24]. Some radio telescopes, particularly those working at low frequencies, make use of dipole antennas instead of parabolic dishes. In these telescopes the "beam" is formed electronically, trading some of the complexity of building a large physical telescope into the back-end hardware and software [29].

A focusing telescope's ability to precisely measure the direction of radiation – its *spatial resolution* – is limited by diffraction of the electromagnetic waves. Self-interference of the waves means that a point source of radiation, observed by a telescope of finite size, will generate an image with a finite size. Details smaller than this size are not detectable. The spatial resolution depends on the ratio of the telescope aperture (its main mirror or lens) size to the wavelength of the radiation, as D/λ. At a given wavelength, a larger telescope will have better spatial resolution, but as wavelengths get larger, telescopes need to be larger to have the same spatial resolution. This is why the largest telescopes are those that work at radio wavelengths. For example, radio telescopes commonly observe at a wavelength of 21 cm to detect radiation from by atomic hydrogen in the interstellar medium. To achieve the same spatial resolution at 21 cm as a visible-light telescope working at 600 nm, a radio telescope needs to be 350,000 times larger! The shape of the telescope surface also must be precise to smaller than the wavelength of the radiation, so visible-light telescopes must be made of a very carefully polished smooth material, but the surface of a radio telescope can be much rougher.

Interferometers, such as the well-known Jansky Very Large Array (Fig. 2), combine the radiation received by multiple telescopes. This achieves the spatial resolution (but not the light collecting power) of a telescope equivalent in size to the distance between the furthest-separated elements of the array. Interferometers can work at many wavelengths, but radio-wavelength interferometers are the most common. This is both because they are more practical to construct than extremely large single telescopes, and because combining radiation at radio wavelengths is technically simpler.

In astronomical measurements the distance to the objects being observed is generally unknown. This means that we can only measure sizes and projected distances in terms of *angular size*, the fraction of a circle measured in angular units (Fig. 3). The Moon and Sun both have angular diameters of about half a degree. The degree is rather large compared to the angular size of most astronomical objects, so smaller units are also commonly used, for example the *arcsecond*, which is $1/3600^{\text{th}}$ of a degree.[4] The angular size of Saturn depends on the distance between Saturn and Earth but averages about 17 arcseconds; distant galaxies have an angular size of a few arcseconds. Many astronomical sources of radiation are so distant that their angular size on the sky is far smaller than the resolution limit of the telescopes we use: the nearest star to the Sun, Proxima Centauri, has an angular size of about 1 milli-arcsecond. We call these *point sources*. Their angular size as observed by a given telescope is the same as the telescope's spatial resolution. In general, detecting details of an object on spatial scales smaller than a telescope's spatial resolution isn't possible,[5] so point sources are just that, pinpricks of light with no structure other than that imprinted by the telescope optics.

[4] If $1/3600^{\text{th}}$ reminds you that a second is $1/3600^{\text{th}}$ of an hour, this isn't a coincidence. The once-a-day rotation of the Earth closely ties astronomical coordinate systems into measurements of time; for more on this concept, see Section 3.

[5] 'Super-resolution' methods are only occasionally used in astronomy: they require a detailed knowledge of the instrumentation, and most importantly, a level of signal-to-noise which is often not available.

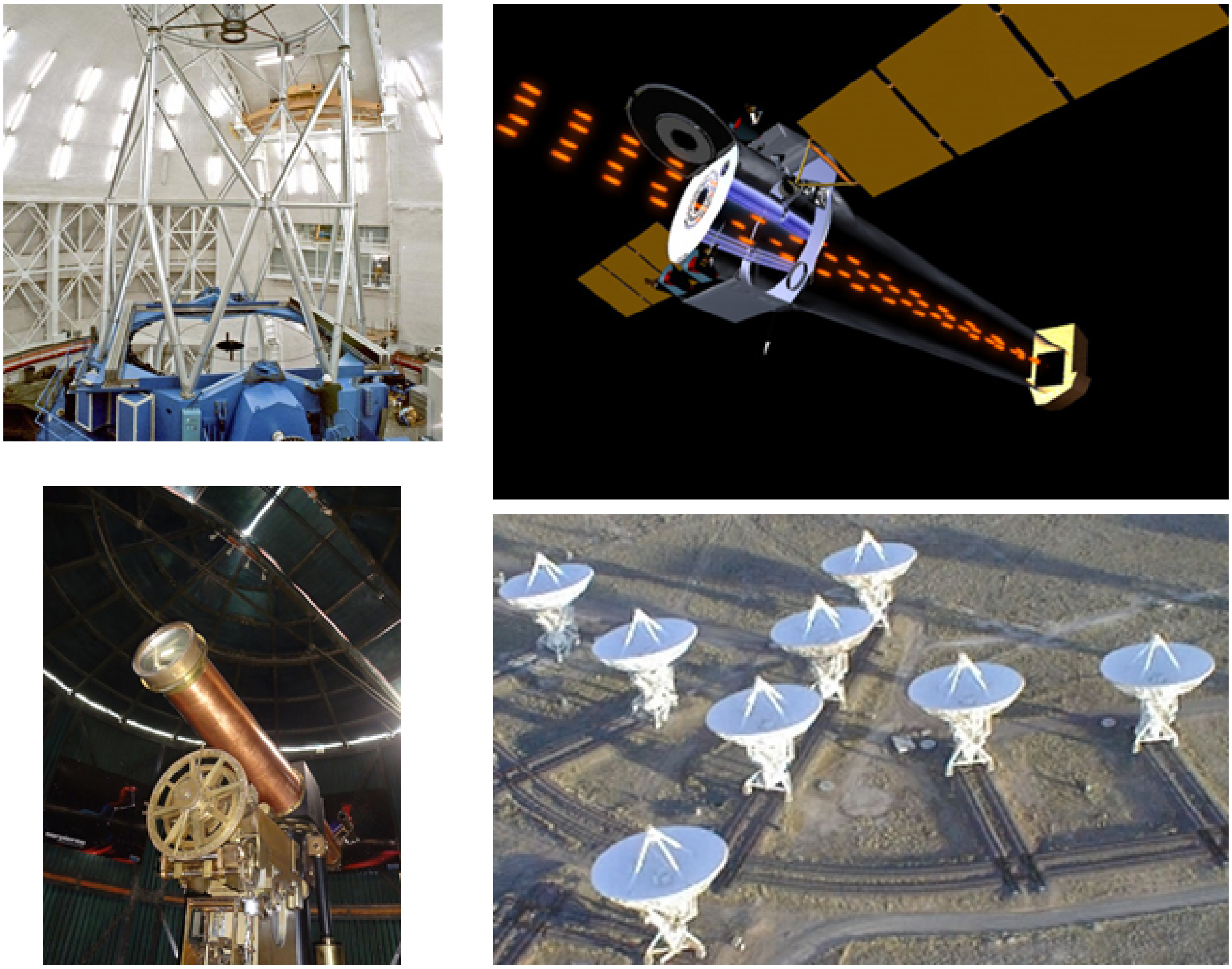

Figure 2: Astronomical telescopes. Clockwise from upper left: reflecting visible-light telescope, reflecting X–ray telescope (note that X-rays must strike the surface at a very shallow angle to be reflected), reflecting radio telescopes linked as an interferometer, refracting visible-light telescope. Credits: Gemini Observatory/AURA, NASA/CXC/D.Berry, NRAO, David Alan Kess via Wikimedia Commons.

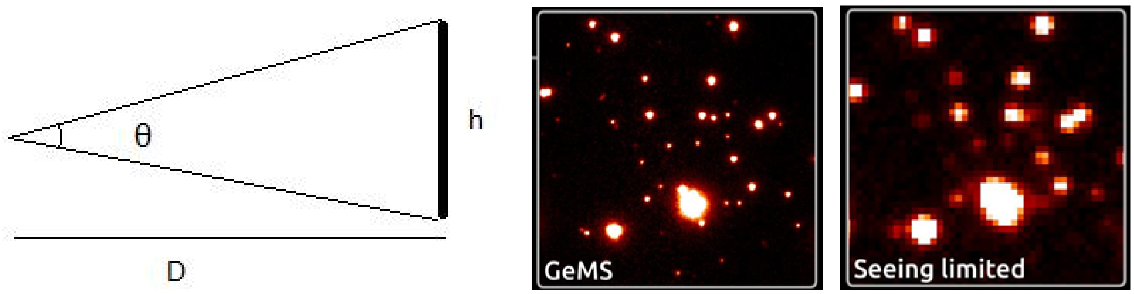

Figure 3: Angular size and angular resolution. Left: in astronomy, angular size θ is easily measured while physical size h and distance D are usually unknown. Right: the effects of improved angular resolution shown by images of the same portion of the star cluster NGC 288 made with (far right) and without (center) the Gemini telescope's GeMS adaptive optics system. Credits: N. Lantz via Wikimedia Commons, Gemini Observatory/AURA.

3 The Earth and its atmosphere get in the way: observatories and the sky

Observations with telescopes located on the Earth's surface are affected by the atmosphere. Turbulence induces refraction of radiation which slightly changes its direction. The net effect of these slight changes is to blur images of point sources such that their angular sizes are larger than they would be without the atmosphere, a phenomenon called *seeing* which is relevant at infrared and smaller wavelengths. This reduction in spatial resolution spreads out the light from unresolved objects, reducing the signal-to-noise of measurements and the ability of telescopes to see detail in resolved objects. Seeing is affected by weather and airflow over the surface of the Earth, so it varies with location: professional telescopes are built in locations where climate and topography combine to yield very good seeing, such as Maunakea on Hawai'i or the Atacama desert in Chile. Seeing also varies with time and direction in the sky, often on a minute-by-minute basis. Space telescopes are unaffected by seeing, and this is the major reason why the Hubble Space Telescope has been such an important facility over its now more-than-20-year lifetime. *Hubble* is not the biggest visible-light telescope, by far, nor is it closer to astronomical objects in any meaningful way, but being above the atmosphere improves its spatial resolution which is incredibly useful.

Overcoming the effects of the Earth's atmosphere can be done to some extent with *adaptive optics*. This technology involves monitoring the seeing by rapidly measuring the shape and size of a reference point source, then compensating for it using a deformable mirror that bends light in the opposite direction to what the atmosphere is doing (see Fig. 3). Bright stars can be used as references, but because seeing varies with direction, that limits the objects whose images can be corrected to those near a bright star on the sky. It's also possible to create *artificial stars* by bouncing a laser beam off the Earth's upper atmosphere [34]; this allows adaptive optics to be used over a greater fraction of the sky.

The other major effect of the Earth's atmosphere on astronomical observations is to entirely block some wavelengths of light. The atmosphere is transparent only to visible light, radio waves, and some wavelengths in the ultraviolet and infrared regions of the spectrum. The transparency of the atmosphere also varies with altitude and (at some wavelengths) the amount of water vapour, meaning that high, dry sites are favorable. Many types of radiation cannot pass through the atmosphere (Fig. 1): detecting, for example, X–ray or ultraviolet radiation from astronomical objects requires a telescope in space. Most space telescopes are in orbit around the Earth, but some telescopes need to be not only *above* the atmosphere, but *away* from it. The Earth and its atmosphere absorb radiation from the Sun and emit copious amounts of infrared radiation, making it very difficult for even space telescope in Earth orbit to detect faint infrared radiation from distant objects. A solution first used for the *Spitzer* Space Telescope is to place infrared telescopes in a *solar* orbit at about the same distance as, but far away from, the Earth [17]: the Sun is far enough away that its angular size is small and a telescope can simply look in the opposite direction.

Infrared light from the Earth and its atmosphere is not the only kind of "light pollution" affecting telescopes. While the infrared sky is bright all the time from the Earth, the visible-light sky is only bright during the day. That the sky is blue during the day and black at night is a fact of life to those of us who live on Earth, but a visible-light telescope on the Moon, for example, could observe with the Sun above the horizon because the Moon has no atmosphere to scatter sunlight. Even from the moon, or space, the Sun's brightness compared to all other sources of radiation from space means that it's nearly impossible to observe objects which appear close to the Sun in the sky. Objects which are located along the Sun's apparent path through the sky due to the Earth's orbit–the *ecliptic*—are observable only at certain times of year (Fig. 4). Similarly, objects close to the Moon in the sky are also not usually observable, and some types of observations by Earth-based telescopes are also affected by scattered moonlight and can't be done when the Moon is visible. Unlike visible-light and infrared telescopes, radio telescopes on Earth can also observe during the day and through clouds, at least at some wavelengths.

A third type of light pollution, and the usual use for the term, is the kind generated by humans. Satellites, spacecraft and aircraft make occasional appearances in astronomical observations but are usually only a nuisance. More significant is the effect of human-generated visible light sources on the ground [18]. Their encroachment is one reason why professional telescopes are often built in remote locations. Human-generated radio emission makes radio astronomy completely impossible at many wavelengths [2]; special protected bands have been established at particularly important wavelengths (e.g., emission from atomic hydrogen in the Milky Way). Removing the effects of radio-frequency interference (RFI) on astronomical observations is a substantial effort which is expected to become more important as new, larger telescopes come online and the use of wireless communications technologies increases.

While some telescopes can observe through the Earth's atmosphere, the types of telescopes we are discussing here can't see through the Earth, meaning that they can only observe objects which are above the horizon. As discussed above, the location of the Earth in its orbit determines which part of the sky is in the opposite direction to the Sun and therefore visible at night. Location of an observatory on Earth determines which portion of the night sky is visible: for example, an observatory at the South Pole can never observe the north star because the Earth is always in the way (see Fig. 4). An observatory at the equator can see the whole sky over the course of one year. However, unfavorable weather conditions mean that few major observatories are located on the Earth's equator: clouds and precipitation prohibit most ground-based astronomical observations! Observatories located in space don't have to contend with rain or snow, but "space weather," including magnetic activity on the Sun and micrometeroid damage from meteor streams, is occasionally an issue.

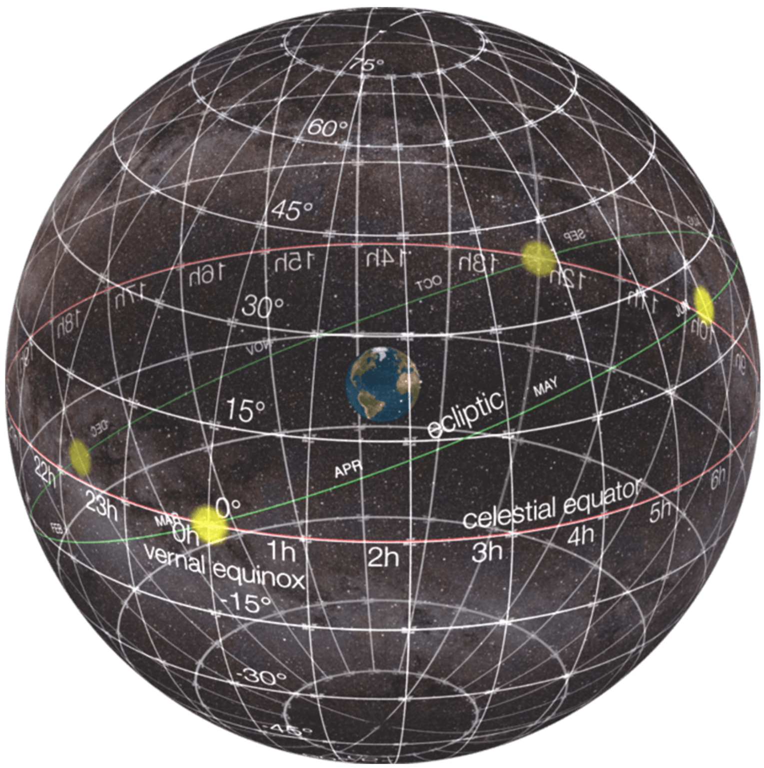

Figure 4: Astronomers visualize sky positions as locations on the "celestial sphere." Objects beyond our solar system change their positions only very slowly, while objects within the solar system appear to change positions due to their own orbits and that of the Earth (e.g. the Sun's path through the sky, known as the "ecliptic" and shown as a green line.) Observers on Earth see different portions of the celestial sphere depending on location and time of year. Credit: C. Ready via Wikimedia Commons.

4 Capturing the light: instruments and detectors

Telescopes collect radiation and focus it, but this is only the first part of making an astronomical observation. The next part is measuring that radiation: how much? what wavelength? where? when? In astronomy, the devices that are used to make these measurements are called *instruments*; many telescopes use multiple instruments, each specialized for different purposes. In a modern observatory the instruments can be more complex and expensive than the telescope itself. The first step in measurement is detection, that is, ensuring that a "signal" (radiation from an astronomical object) is statistically unlikely to be a random fluctuation of noise (radiation from the telescope or instrument, a natural background such as the atmosphere or Milky Way galaxy, or human-generated interference). Astronomical observations are very often signal-to-noise limited and carefully estimating the noise so as to evaluate the significance of a detection is a common procedure. Astronomers often work with what statisticians call *censored* observations, where the precise value for a quantity cannot be measured but can be constrained to be below some quantitative limit. Unlike in many scientific fields, such "non-detections" are considered suitable for publication!

When faint sources of radiation are being observed, signal must be collected over a long period of time. As with conventional photography, this period is called the *exposure time*, but where photographic exposure times are usually fractions of a second, astronomical exposure times can be minutes or hours. Exposures of more than a few seconds require a telescope to be *guided* to offset the apparent motion of celestial objects due to the telescope's position on a rotating, orbiting Earth or an orbiting spacecraft. Exposure times are chosen to be long enough to achieve desired signal-to-noise of the measurements, which depends on the rate at which photons are received from the source and background (S and B, respectively). Usually we want to measure s and estimate its uncertainty: the ratio of these two quantities is the signal-to-noise ratio (SNR) and can be shown to be $\mathrm{SNR} = S/\sqrt{(S+B)/t}$. A key point is that signal-to-noise increases as $\sqrt{t}$, meaning that increasing the SNR of a detection by a factor of two requires observing for four times as long. The equation above assumes no uncertainty in background measurement or other systematic uncertainties, which is almost never the case in practice.

The simplest type of measurement is *imaging*: as in everyday cameras, radiation from the telescope is focused on a *detector*. In the earliest days of astronomical imaging, visible-light detectors were photographic film or plates, but now visible-light and essentially all astronomical detectors are semiconductor-based digital devices. The details of the detectors vary with the wavelength involved: for example, X–ray detectors can often measure the energy and arrival time of each incoming photon. Ultraviolet, visible-light, and infrared detectors can't do this and must use optical filters to measure only certain wavelengths at a time, and a series of images to measure brightness over time. Detectors can have from one to hundreds of millions of picture elements, or pixels (see Fig. 5), depending on many factors including the optics of the telescope and limits of the detector technology. The Megacam instrument on the Canada-France-Hawaii Telescope, commissioned in 2003, has 340 megapixels and produces a typical raw data volume of $\sim$ 100 GB per night [14]. The camera on the future Large Synoptic Survey Telescope (LSST) will have over 3 gigapixels and produce tens of terabytes of raw data per night [16].

Radio astronomy differs from visible-light and infrared astronomy in how detectors work. At wavelengths of about 1 mm or larger, detection is *coherent*, meaning that the phase of the incoming radiation is measured by interfering the astronomical signal with a locally generated wave. (At smaller wavelengths we say that detection is *incoherent*.) The fundamental reason for using coherent detection at long wavelengths λ is to reject thermal noise, which would otherwise dominate any astronomical signal: the thermal noise is incoherent so is not detected. Most coherent detectors have only a few pixels, so mapping an extended source requires making measurements with many pointings of the telescope, or reconstructing the sky brightness distribution with interferometry. Technological limitations mean that long-wavelength spectroscopy (see below) is feasible only with coherent detection, and interferometry is also more straightforward with coherent detection. Because radio interferometers must store the correlated signals from all antenna pairs, densely sampled in both time and frequency domains, they produce substantial data volumes with substantial computational challenges [23]. Typical data rates for the Jansky Very Large Array are tens of MB per second; the future Square Kilometer Array radio telescope will produce raw data at a few TB per second, or PB per day [10].

5 Data processing and measurements

Recording astronomical observations with digital detectors is only the first step in the measurement process. The data stream from the instruments generally has to be processed to remove instrumental signatures and calibrate the measurements into physical units. The procedures for this are standardized to some extent, but since astronomical instruments are typically bespoke and customized to an individual telescope, each instrument has its own idiosyncracies. Calibration of instruments can involve a combination of laboratory testing, observations of standard sources, and cross-checks with other instruments. Factors that need to be calibrated include *spatial response* (correspondence between where an object appears in an image and its true position on the sky) and *sensitivity* (conversion of detector counts to physical units of energy such as Watts). Both spatial response and sensitivity can depend on characteristics of the instrument or atmosphere (e.g., temperature, humidity) as well as the detected radiation (e.g., wavelength, brightness).

Processing (often called *reducing*) astronomical data requires detailed knowledge of the instrumentation, understanding of a particular observation's science goals, and scientific judgment. Some observatories, particularly facilities with many users, provide 'data pipelines' to automatically reduce data from their instruments; others expect their users to process their own data. Interferometric observations in radio astronomy produce such huge data volumes that customized hardware, as well as software, is required for data processing [33]. Commercial image-processing software is typically only used in astronomy to produce images for visualization or public relations. For scientific analysis, astronomers prefer to use open-source software so that they know exactly what is being done to their data and are reassured that the characteristics of the physical measurement are preserved.

The result of astronomical data reduction is a 'science-ready' data product with which photometric or spectroscopic measurements can be made. This data product may be in the form of a one dimensional spectrum, a two-dimensional image or spectrum, or a three-dimensional data cube with the three dimensions being two sky coordinates and wavelength (Fig. 5). Astronomy uses a standard file format, FITS (Flexible Image Transport System; [25]) which includes both science data and metadata describing the details of the observation and subsequent processing. Astronomical measurements are generally performed with software designed specifically to deal with astronomy's unique file formats and data conventions, although software written for other purposes (e.g., AstroImageJ [11]) is sometimes adapted. The Astrophysics Source Code Library [1] is a repository with a comprehensive listing of astronomical software. The AstroPy project [5] is an extensive community-developed, still-evolving library of analysis code in the Python language. As with other scientific fields, development of software in astronomy is often not recognized as "doing science" and its practitioners may not receive appropriate career credit [21].

Measurements made on an astronomical image typically fall into two categories: *photometry*

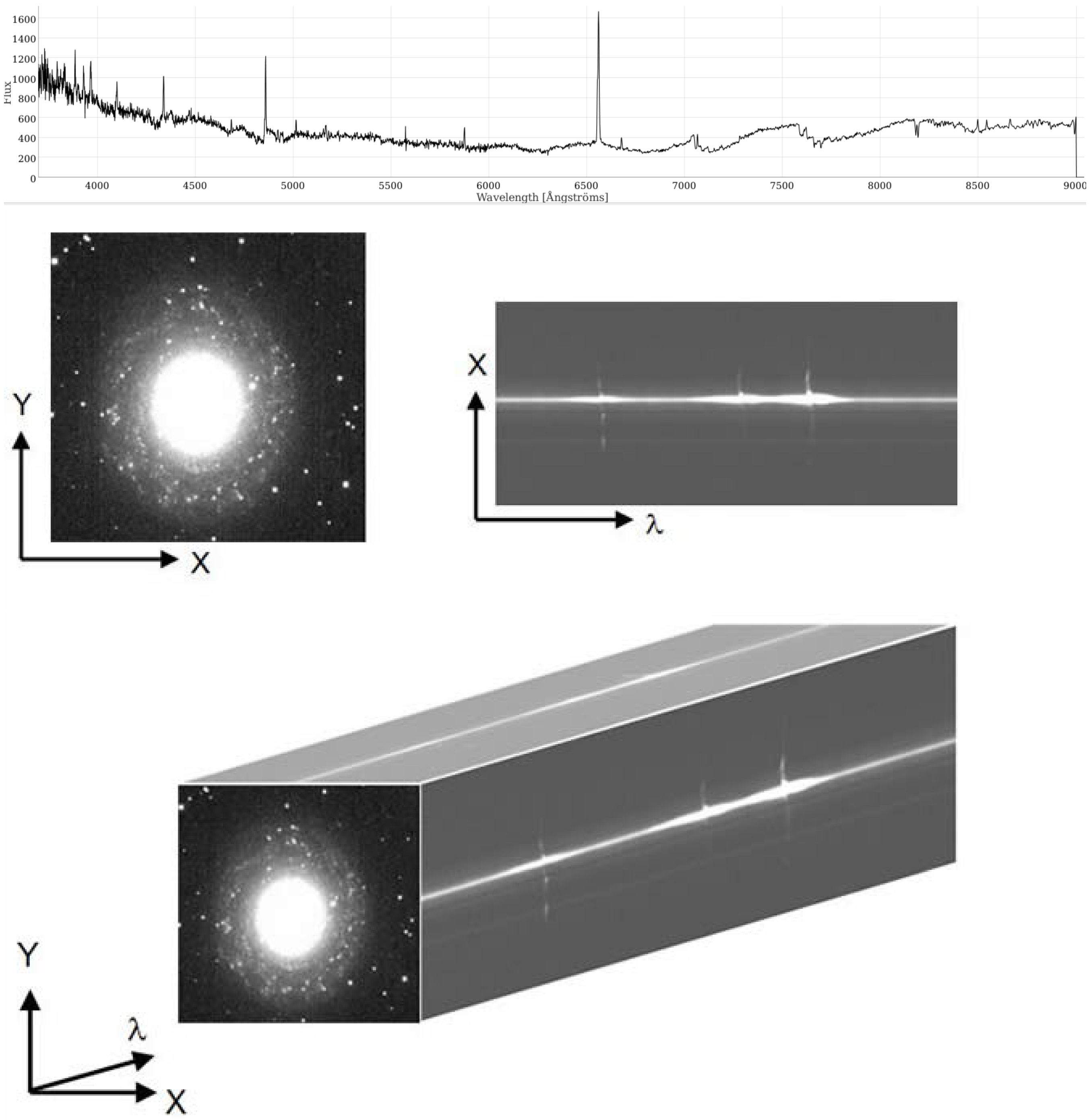

Figure 5: Astronomical measurements: Top: one-dimensional spectrum of a star taken with the LAMOST telescope. Center: notional two-dimensional image and spatially-resolved spectrum. Bottom: notional three-dimensional datacube. Credits: [30], National Astronomical Observatory of Japan.

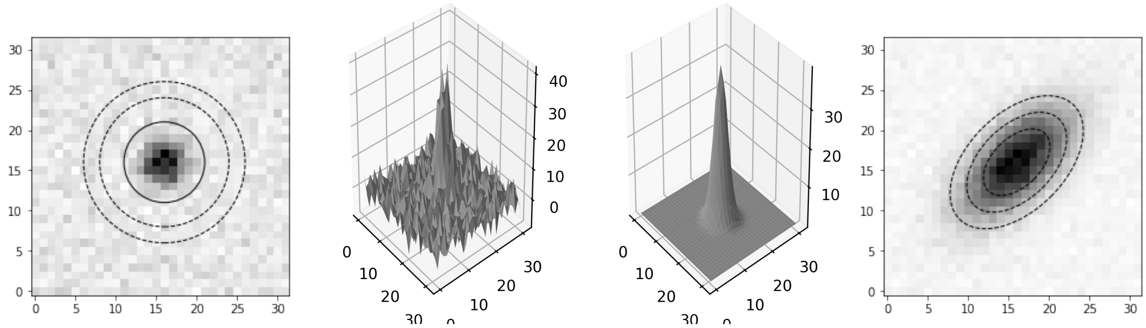

Figure 6: Astronomical photometry. Left: aperture photometry measures brightness by summing the values of pixels within an aperture (solid lines) and subtracting an average background value, measured in a background annulus (dashed lines). Centre: point-spread-fitting photometry measures brightness by fitting a two-dimensional function (center right) to the pixel values (centre left). Right: surface photometry measures brightness as the sum or average of pixel values within concentric circular or elliptical annuli.

and *astrometry*. Photometry involves measuring the amount of energy received at the telescope, either from individual objects or from extended regions within the image. Photometry can be either relative (to other objects in the image) or absolute (in physical units such as W m^{-2}). Absolute photometry requires calibration of the measurements, usually done by comparison to objects of known brightness. Astrometry involves measuring the location of objects on the sky and can also be relative or absolute. Some astronomical objects change position and/or brightness with time, for example asteroids in our solar system or pulsating stars. Measuring those changes requires recording a series of images at different times, with the time intervals between images matched to the expected timescales of change. Timescales relevant to astronomical phenomena range from milliseconds to centuries, depending on the object type, and this hints at major challenges in both data acquisition and data management. The LSST project, one of many that are facing these challenges, is leveraging the experience of large particle-physics experiments to develop the necessary sophisticated computational architecture [16].

Because modern astronomical data is, at its core, an array of numbers, making measurements involves performing calculations on that multi-dimensional array. Photometric measurements are performed on a two-dimensional array representing brightness as a function of sky position (Fig. 6). Measuring the positions of objects involves determining the centre of their light distribution, often assumed to be symmetric. *Aperture photometry* involves summing the pixel values in a (usually circular) region centered on an object of interest. The part of the signal due to the background must be subtracted, which can be done on a global scale or locally near the object. Astronomical objects which are unresolved should all have the same shape on the image, that of the *point spread function (PSF)*, and so another approach to photometry involves fitting a two-dimensional representation of the PSF to the pixels and measuring brightness via the normalization. Compared to aperture photometry, PSF-fitting photometry can have improved signal-to-noise and ability to distinguish nearby objects, but this requires good knowledge of the point spread function which is not always available. *Surface photometry* applies to resolved objects such as galaxies or planets; in this case the desired measurement is the object brightness per unit area, often measured as a function of distance from some fiducial location (e.g., the equator for a planet, or the centre of a galaxy).

For small-wavelength regimes in which the energies of the incoming photons (or precise wavelengths of the incoming waves) are not directly measured by the detector, additional instrumentation is used to disperse the radiation so that different wavelength photons arrive at different locations on a camera's detector. This kind of instrument is called a *spectrograph* and the measurement of brightness as a function of wavelength is *spectroscopy.* A prism is a familiar example of an optical element that disperses light into a spectrum; in astronomical spectrographs, diffraction gratings are more commonly used. In coherent detection, such as with radio radiation, separating wavelengths is performed via *heterodyning* where the incoming radiation is mixed electronically with radiation of a known frequency. Spectroscopy can be either one-dimensional, in which a single spectrum is obtained for an point-source or resolved object, or two-dimensional, in which spectra are obtained for multiple positions within a resolved object (see Fig. 5). As with photometry and astrometry, spectroscopy can be relative or absolute and can also be performed in a time series. Because spectroscopy involves spreading light over more detector elements, the signal-to-noise per detector element is lower than for photometry. This means that spectroscopy typically requires more photons to be collected, either with larger telescopes or longer exposure times or both. Spectroscopy is more technically demanding than photometry but the wealth of information it can provide on composition, motion, and physical conditions in astronomical objects, is incredibly valuable.

Spectroscopic measurements are performed on a one-dimensional array representing brightness as a function of wavelength, or on one-dimensional slices through a data cube. Spectroscopic measurements generally fall into two categories: measurement of *lines* or *continuum* (Fig. 7). Spectral lines are radiation emitted or absorbed at specific wavelengths/frequencies, generated by specific atoms or molecules in the astronomical object of interest or the intervening medium. Line measurements can yield important physical information about conditions within an object, or its line-of-sight motion (via Doppler shift). Identifying the source of a given spectral line is done via reference to laboratory measurements and/or theoretical calculations. Measurement of absorption or emission lines involves measuring their centre, width, and height either on an absolute scale or relative to the nearby continuum. As with PSF-fitting photometry, often the *line profile* is fit to a functional form that accounts for the expected response of the instrument.

Continuum radiation involves a broader range of frequencies than spectral lines and comes from *blackbodies* emitting thermal radiation (e.g. atoms in a stellar atmosphere) or *non-thermal sources* such as electrons in the magnetic field near a pulsar. Measurement of the continuum in a spectrum involves measuring the overall shape of the spectrum over a broad range in wavelength and can be either in absolute units (*spectrophotometry*) or in a relative sense (e.g., measuring a *spectral slope*). Spectroscopic measurements on two- or three-dimensional data extend to determining the above features as a function of spatial position. Spectroscopic time series extend these measurements to also be a function of observation time.

How are astronomical observations used to improve our understanding of the cosmos? While measurements may be purely descriptive, they are more likely to be used in the context of a physical model of the phenomena and processes at hand. This may involve comparing measurements with the predictions of analytical calculations or computer simulations based on the current understanding of physics. Many different areas of physics are relevant to astrophysics, often under conditions (e.g., temperature, density, velocity, magnetic field strength) that do not occur or cannot be replicated on Earth. Comparison of observations with theoretical predictions often points to situations where physical understanding is inadequate, or judgment about the relevant areas of physics is incomplete. Because astronomy is an observational science, with the conditions of observation largely out of the observer's control, consideration of *selection bias* – is very important [20].

Measurements of a large number of objects within a given observation, or set of observations, are often combined into an astronomical *catalog.* Catalogs have been part of astronomy for thousands of years, with some of the earliest catalogs dating from ancient China and Greece. In their modern

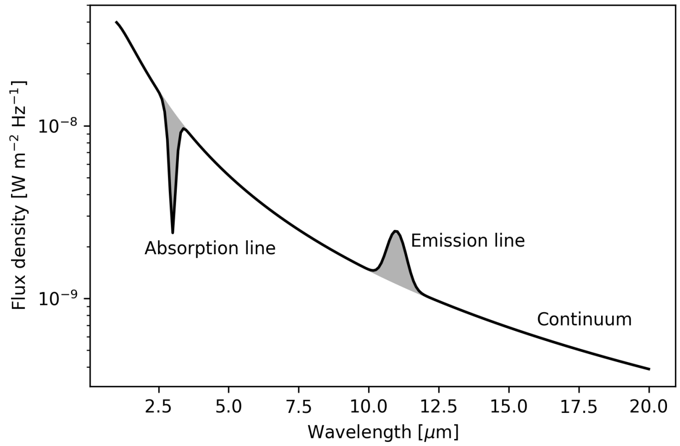

Figure 7: Notional astronomical spectrum showing absorption and emission lines and continuum. Possible measurements of the lines include center, width, depth, or higher-order moments such as skew; possible measurements of the continuum include its slope and/or absolute level.

implementation, catalogs are published in the astronomical literature as tables within articles, if small, or made available online as databases, if large. They can results from surveys of the entire sky, studies of a specific set of objects in a particular region, or anything in between. Examples range from C. Messier's catalog (1781) of just over one hundred extended celestial objects, including galaxies, nebulae and star clusters, to the Two Micron All-Sky Survey catalog (2001) of over 500 million stars and galaxies detected at near-infrared wavelengths [31]. While most astronomical catalogs result from deterministic data processing pipelines, new approaches to constructing catalogs based on Bayesian inference are beginning to emerge [15, 27].

Analysis of astronomical catalogs can involve characterizing the relationships between properties of the catalogued objects, measuring the joint distributions of specific properties, and searching for outliers in feature space. To facilitate this analysis, astronomers are beginning to embrace sophisticated database methods, including the use of Structured Query Language (SQL), spurred on by the advent of the Sloan Digital Sky Survey and other large projects. As in many other scientific fields, astronomers are rapidly expanding their use of machine learning, with topics such as classification and multi-wavelength cross-matching being of particular interest. Real-time classification of time-variable events will be especially important for upcoming facilities such as LSST [e.g. 22].

Allocation of telescope time for observations is performed via peer-reviewed competitive selection. Broadly-speaking, observational programs fall into two modes: *PI (Principal Investigator)* or *survey*. In the former, the telescope is used for a specific program of investigation on one or more objects, defined and executed by a small team. In the latter, a (typically larger) team defines a project to survey a specific area of sky or sample of objects, with the intention of making data products available for use by the team and other interested astronomers. Many space missions, such as WISE [35] or Gaia [13], were designed as perform survey programs. Ground-based telescope survey projects are somewhat newer; the game-changing example of such is the Sloan Digital Sky Survey [12]. For both types of projects, the proposing team typically retains exclusive rights to the raw observational data for a limited period of time (a few months to a few years) after which the data become publicly available through an online *archive*. Archives are incredibly valuable sources of information: the data in telescope archives can often be used for purposes other than specified in the original proposal. For example, more papers are now published with archival data from Hubble

Space Telescope observations than with data from “new” proposals [4]. A culture of data-sharing is well-established in astronomy but barriers remain in tapping the full potential for distribution and re-use of observations [26].

6 Conclusions

Astronomical observations are a major way in which we understand the universe beyond the Earth. The vast distances of the objects under study mean that we receive only a small amount of radiation from them, and the technical challenges involved in making measurements from this radiation and turning it into knowledge are substantial. Maximizing the effectiveness of astronomical facilities requires state-of-the-art technology in both instrumentation and computation.

For centuries, visible light was astronomers’ only source of information about the universe. In the twentieth century, observational astronomy matured in its use of other forms of electromagnetic radiation and began to explore other messengers of the cosmos. Particle and gravitational-wave observatories (sometimes referred to as ‘multi-messenger astrophysics’ [3, 6, 7]) are just beginning to yield new information inaccessible through other means. Astronomers are fortunate to be able to expand our understanding using these methods, the next generation of electromagnetic observatories, and new approaches to understanding the information they produce. In the past, each new technique or observational regime has yielded new discoveries, and we can hope that future new facilities will produce equally exciting results.

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