Theme 10: Beyond the Visible II:

the impact of space exploration on astronomy

The launch of Sputnik 1 in 1957 heralded a new era for astronomy. Up to that point, astronomers had been restricted to what they could observe from the Earth (with a small contribution from high-altitude balloons and sounding rockets, which were limited in both their payloads and the maximum observing time). The advent of the Space Age has revolutionised much of astronomy—not only as regards the solar system, which we can now explore physically, but also by the windows opened on the wider universe.

The advantages of space-based instrumentation essentially fall into three categories:

- direct exploration of the solar system by fly-bys, orbiters, landers and—for the Moon—manned and unmanned sample-return missions;
- observation at inaccessible wavelengths such as X-rays, UV, far infra-red etc.;
- high precision imaging at "normal" wavelengths, but without atmospheric turbulence.

10.1 The Solar System

The most obvious impact of space exploration is on our knowledge of the solar system. A respected general textbook of the 1960s (Motz and Duveen, *Essentials of Astronomy*) devotes only a single 30-page chapter to "Properties of the Planets", and about a third of this is basic information about their orbits, diameters and masses. The Jovian satellites get two paragraphs, and Saturn's get one. A similarly respected textbook of the 1990s (Carroll and Ostlie, *Introduction to Modern Astrophysics*) devotes 150 pages to the planets, almost none of it basic information. Some of the difference is due to advances in general understanding—for example, an extended discussion of plate tectonics on Earth—but most of this enormous increase in understanding is a consequence of unmanned missions to the different planets.

Main programmes

Planetary exploration started very quickly, with the Russian Luna 2 crash-landing on the Moon in 1959, and Luna 3 imaging the lunar far side in the same year. Both the Russian and the American space programmes explored the inner planets in the 1960s and 70s, with the Russians generally focusing on Venus (after an ambitious Mars programme came unstuck as a result of minor but disastrous faults—e.g. a faulty computer chip which severely limited the data return) and the Americans more interested in Mars.

Luna

The Luna programme (1959–1973) was a long series of Russian Moon missions, which started with crash-landings, progressed to orbiters and soft-landers (Luna 9 being the first ever soft-landing somewhere other than the Earth, in 1966), and eventually to unmanned rovers (Luna 17 and 21, 1970 and 1973) and sample-return missions (Luna 16, 20, 24, 1970–72). It was obviously overshadowed by the American Apollo programme (for example, it returned about 330 g of lunar rock samples, whereas the American managed about 380 kg) but achieved a number of "firsts", including first images of lunar far side, first lunar orbiter, first soft landing, first unmanned rover, first unmanned sample-return. In many ways, the Luna programme is a more obvious ancestor of today's scientific spacecraft than Apollo.

Venera

Venera (1961–1984) was the USSR's Venus exploration programme. In many ways it was more advanced than the contemporary American Mariner series, with an emphasis on landers and atmospheric probes right from the beginning. The vicious environment on Venus (temperatures of 730 K and pressures of around 90 atmospheres) led to an extremely short lifetime for most of the landers, and consequently a rather limited amount of data gathering; this was exacerbated by the fact that the mother-ships were flybys and not orbiters, so that in some cases the lander was still transmitting when the mother-ship went out of range.

There were also a few design faults with unfortunate outcomes (the entire series had problems with the camera lens caps, which led to complete camera failure on several missions; in one case where the lens cap did come off it landed exactly in the path of the soil analysis probe!). However, the programme as a whole was impressively successful, with many measurements of the atmospheric and soil chemistry of Venus, and a pair of highly successful radar mappers (the Venus orbiters Venera 15 and 16, 1983). The final two Russian Venus missions, Vega 1 and 2 in 1985, also deployed balloon-borne instrument platforms ("aerostats") to investigate the high atmosphere: these settled at an altitude of around 53 km and were still going when their batteries ran out.

The Venera 15 and 16 radar mappers inspired a later American mission, the immensely successful 1989 radar mapper **Magellan**. Magellan produced an almost complete map of the surface of Venus, with 100 m resolution (about ten times better than Venera's), and a map of Venus' surface gravity (created by having the spacecraft transmit a carrier wave at a fixed frequency and using the Doppler effect to measure small changes in its orbital speed). Magellan has the possibly dubious distinction of being the first planetary probe launched from the Space Shuttle.

Mariner

The US Mariner programme was a series of flyby missions running from 1962 to 1975: four were aimed at Venus (three of them worked) and six at Mars (four worked, including one orbiter). The most spectacular result of the Mariner missions was probably the unexpectedly cratered Martian terrain imaged by Mariner 4. Mariner 9, the sole orbiter in the programme, followed up on this with a detailed map of the entire Martian surface: Valles Marineris ("Mariner Valley") was named for Mariner 9. Mariner 10 also deserves credit for being, until Messenger in 2008, the only mission ever to have made a close approach to Mercury—three fast flybys in 1974 and 1975—and for being the first probe to make use of what later became the standard technique of using a gravitational assist from one planet to reach another (in this case, from Venus to Mercury). Besides images, the Mariner missions returned information on rotation rates, temperatures (using microwave and infra-red radiometers), magnetic fields (using a magnetometer), and the solar wind.

Lunar Orbiter

Lunar Orbiter (1966–7) was a spectacularly successful series of photographic mapping missions intended to prepare for the Apollo landings. Like most of the early photographic satellites, the Lunar Orbiter missions used film cameras (much better resolution than TV), and had to carry an automated wet chemistry lab to develop the film, which was then scanned for transmission. The images are now available online at http://www.lpi.usra.edu/resources/lunar_orbiter.

Viking

The US Viking probes (1975) were orbiter-lander combinations. This (unlike the largely ill-fated Soviet Mars programme) was a highly successful mission: both landers survived and returned data for several years, as did the orbiters. Most of our understanding of Mars was based on Viking for 20 years, until the success of the Mars Pathfinder lander and the Mars Global Surveyor orbiter in 1996. The orbiters were photographic mappers; the landers studied atmospheric and soil chemistry and meteorology, and deployed seismometers to look for geological activity. Several of the soil chemistry experiments were specifically designed to look for biological activity. These produced ambiguous results, with some experiments apparently seeing activity while others did not. Overall, the mainstream opinion is that the "positive" results were produced by unusual but not biological chemical reactions, most likely involving a strong oxidising agent produced by the action of UV radiation on Martian soil, although a few of those involved still think that the results indicate a small amount of organic activity.

After Viking, there was a long hiatus in Mars exploration, partly as a result of a genuine lack of interest and partly because several intervening missions failed. In the 20 years, interest has been revived, with the very successful Pathfinder lander (using the now standard technique of parachutes and airbags, rather than the lunar lander-style rockets employed by Viking) and the even more successful Mars Global Surveyor orbiter (both in 1996), the Mars Odyssey orbiter (2001) and more recently the European Mars Express orbiter (2003), the US *Spirit* and *Opportunity* rovers (2004), the Mars Reconnaissance Orbiter (2006), the polar lander *Phoenix* (2008; successor to the ill-fated Mars Polar Lander, which crashed in 1999), the *Curiosity* rover (2012) and the MAVEN orbiter (2014).

A striking addition to the list is the Mars Orbiter Mission *Mangalyaan*, which entered orbit in 2014. Though not particularly advanced in scientific terms (it was intended primarily as a technology demonstrator), it is noteworthy because it belongs to the Indian Space Research Organisation and was delivered entirely by Indian technology (it was launched from India using an Indian-built rocket)

10.1.2 The outer solar system: Pioneer and Voyager

The most spectacular success of the solar system exploration programme was the increase in our understanding of the outer solar system. This programme started in the early 1970s with Pioneer 10 (launched 1972) and 11 (launched 1973). Pioneer 10 was a Jupiter flyby; Pioneer 11 was a Jupiter flyby with gravitational assist to Saturn. Both were also explicitly intended to pave the way for the more ambitious Voyager probes, in particular by demonstrating that passage through the asteroid belt was possible without damage. Unlike missions to the inner solar system, which are generally powered by solar cells, the Pioneers were powered by a thermal pile, which uses radioactive decay to generate power.

Pioneer 10 made extensive measurements of the Jovian magnetosphere, discovered Jupiter's ring system, improved our understanding of the masses of Jupiter and its Galilean satellites, and discovered that Jupiter gives out more heat than it receives from the Sun. Pioneer 11 carried out essentially the same magnetic field and heat balance measurements for Saturn, produced a similar improvement in our knowledge of Saturn's mass and those of Titan and Rhea, and discovered Saturn's F ring and the satellite Epimetheus.

Both also studied the solar wind; these measurements continued long after the planetary encounters, and extend out to 47 AU.

The two Voyager missions, launched within days of each other in 1977, were intended to take advantage of a favourable configuration of the outer planets which allowed successive gravitational assist manoeuvres. Voyager 1 visited Jupiter and Saturn; Voyager 2 traded a more distant view of Jupiter for a trajectory which also gave it flybys of Uranus and Neptune. Both were exceptionally successful missions, producing not only stunning imagery but also a wealth of scientific data including numerous new satellites, details of the structure of the ring systems of the outer planets, more information of magnetic fields and meteorology, and—perhaps most unexpected of all—information on the striking diversity of the individual natural satellites, including cryovolcanism on Io, Ganymede's magnetic field, Europa's ice crust and Miranda's extremely strange surface features.

Taken together, the four "Grand Tour" missions of the 1970s completely revolutionised our view of the outer solar system. While much valuable detail has since been added by the *Galileo* Jupiter orbiter (soon to be augmented by *Juno*) and the *Cassini*/*Huygens* Saturn mission, it was the Pioneer and Voyager probes which really opened up this region for study.

10.1.3 Small planets and minor bodies

By the end of the 20th century, all the major planets of the solar system had been investigated by spacecraft, with the partial exception of Mercury, which had received only a single fast flyby. This was remedied by the *MESSENGER* probe, which conducted three fast flybys of Mercury (two in 2008 and one in 2009) before entering Mercury orbit in 2011; it crashed into Mercury in 2015 after running out of propellant.

Mercury is the smallest of the major planets (it is smaller than some of the largest moons). The solar system also contains a host of minor bodies—dwarf planets, comets and asteroids—which have also been investigated by space-probes. This programme began in 1985 with the diversion to comet Giacobini-Zinner of a satellite intended to study the interaction of the solar wind with the Earth's magnetic field: it executed a flyby at a distance of 7800 km. The return of the solar system's most famous comet, P/Halley, in 1986, though disappointing from an amateur observer's perspective, sparked a flurry of interest: five flyby missions were sent to intercept it, with the closest, *Giotto*, coming within 600 km and subsequently visiting another comet, Grigg-Skjellerup. Since then, several further comets have been visited, culminating in the 2014 *Rosetta* mission, which actually went into orbit around comet Churyumov-Gerasimenko and dispatched a (not entirely successful) soft-lander, *Philae.*

Several main-belt asteroids have been visited by spacecraft, starting with a 1991 flyby of 951 Gaspra by *Galileo* en route to Jupiter and culminating in the *Dawn* mission, which orbited 4 Vesta in 2011−2012 and is now in orbit around 1 Ceres. In addition, the near-Earth asteroids 433 Eros, 4179 Toutatis and 25143 Itokawa have been visited, Eros and Itokawa both by landers (the Japanese probe *Hayabusa*, which landed on Itokawa, returned samples to Earth—and no, it's not a coincidence that a Japanese probe visited an asteroid with a Japanese name; Itokawa had not been named when *Hayabusa* was launched).

1 Ceres is now officially not an asteroid, but a dwarf planet. The other dwarf planet to have been visited so far is Pluto: the *New Horizons* probe executed a fast flyby of Pluto in July 2015 and is intended to execute a fast flyby of another Trans-Neptunian Object, the classical Kuiper belt object 2014 MU69, in 2019. (Launched in January 2006, *New Horizons* has the dubious

distinction of having been launched as a mission to a planet but completing a mission to a dwarf planet, Pluto having been demoted in August 2006 when it was already en route!)

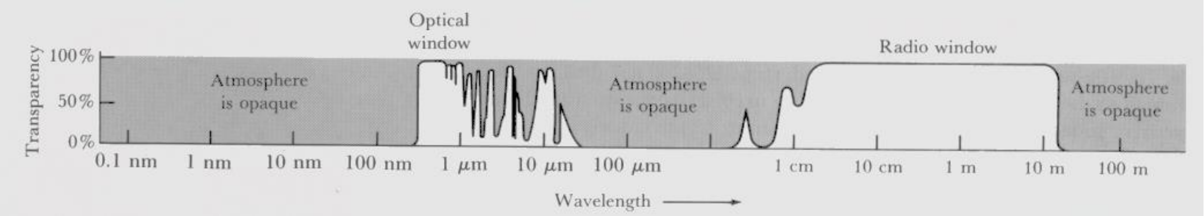
10.1.4 Summary

It is not an exaggeration to say that practically everything we know about the physical properties of the planets, particularly the outer planets and their satellites, has been learned from space missions. The disadvantages of a limited instrument package and a certain lack of flexibility are more than compensated by simple physical proximity. This situation is likely to continue for the foreseeable future. A key advantage of space missions is their ability to make physical contact with the body in question: for example, it is difficult to learn anything about the liquid water oceans believed to lie beneath the surfaces of many icy moons simply by observing them from Earth or Earth orbit, but a space-probe could deploy ice-penetrating radar to confirm their existence, or even a drill to take samples.

Although space missions have made unexpected discoveries—the classic case being Mariner 9's discovery of the cratered surface of Mars—they generally represent Kuhnian "normal science": the instruments and mission profile have to be specified well in advance, and if unexpected results *are* found the craft may not have the equipment necessary to investigate further. An example of this is the somewhat inconsistent results of the Viking mission's biological experiments: a labelled-release experiment which injected organic molecules tagged with ^{14}C into a sample of Martian soil and looked for the release of $^{14}CO_2$ from microbial metabolism had a positive result, while two other experiments (a gas chromatograph/mass spectrometer looking for organics and a gas-exchange experiment looking for evidence of metabolism) were negative. If this happened in a terrestrial lab, one would do more detailed experiments, but this option was not open to the Viking scientists. (It is generally accepted that the positive result was due to unforeseen non-biological chemical reactions, though there are still a few people—including, not entirely surprisingly, the designer of the Labelled Release experiment—who believe otherwise.) This is in contrast to space-based observatories, which tend to be more flexible (because the instruments are usually designed to be less specialised, to suit a broader user community) and have often produced unexpected discoveries.

10.2 Extending the Electromagnetic Spectrum

The diagram below shows the transmission of electromagnetic radiation through the Earth's atmosphere.



The atmosphere is only really transparent in two regions, the optical window (which also extends into the near infrared), which we and most other animals have been using for the last few hundred million years, and the radio window, which astronomers have exploited since the end of WWII. By siting instruments on high mountains and in very dry areas (e.g. the Atacama desert and the South Pole), it is also possible to observe in carefully selected wavebands in the infrared—much of the absorption of infrared is due to water vapour. However, the high energy region (UV, X-rays and γ-rays) is entirely inaccessible from the ground, being absorbed by the upper atmosphere, and so is the region extending from the far IR to the submillimetre. (Long wavelength radio, which is also inaccessible, is extremely difficult to exploit for astronomy because of the inherently awful resolution: arcsecond resolution at wavelengths of 100 m would require a 20,000 km baseline interferometer!)

10.2.1 Short wavelengths

Ultraviolet

Below about 320 nm, radiation is absorbed by the ozone layer, which is high enough to make observation from space essential. On the other hand, techniques for imaging using UV light are relatively straightforward (unlike x-rays). UV astronomy was therefore an early target for space-based instrumentation, with the first UV astronomical satellite, the Orbiting Solar Observatory (obviously devoted to observing the Sun) launched by NASA as early as 1962. General UV astronomy started with the Orbiting Astronomical Observatory series of satellites (four, but only two actually worked) launched between 1966 and 1972, and continued with the immensely successful UK/ESA/NASA International Ultraviolet Explorer (IUE). Launched in 1978 with a projected 3-year lifespan, IUE actually took data until 1996 (and was then switched off, while still working perfectly, as a result of financial pressures): this makes it arguably the longest-lived astronomical satellite to date (HST has operated for longer, but has had several major servicing missions which have involved replacement of all the instrumentation).

IUE was a very productive instrument with both imaging and spectroscopic capabilities, covering the wavelength range 118−320 nm. It made extensive measurements of massive stars (which emit predominantly in the UV), active stellar atmospheres, supernovae, starburst galaxies and active galaxies, and even comets and planets (it discovered Jupiter's aurorae); by 2001 well over 3500 scientific papers had been published based on IUE data. Unlike HST, IUE was placed in a geosynchronous orbit which allowed it to deliver its data to its ground station round the clock: this made using IUE very like using a ground-based telescope—a good thing in an era when most astronomers were unfamiliar with space-based instrumentation.

Since IUE's termination, there have been three further satellites specialising in UV. The Extreme Ultraviolet Explorer (EUVE) overlapped with IUE, operating from 1992 to 2001; as its name suggests, it covered very short wavelength UV (7−76 nm). FUSE, the Far Ultraviolet Spectroscopic Explorer, was launched in 1999 and took data for 8 years until its pointing system failed in July 2007. FUSE was complementary to IUE and EUVE, covering the wavelength range 90−120 nm. It studied similar topics to IUE, with an additional focus on the ratio of deuterium to hydrogen (an important datum for Big Bang nucleosynthesis). GALEX, the Galaxy Evolution Explorer, launched in 2003 with a planned lifetime of 2½ years, was essentially an updated IUE: the wavelength range covered was 135−280 nm and it had imaging and spectroscopic capabilities. Like IUE, GALEX exceeded its planned lifetime by a considerable margin and was switched off for financial reasons (in 2013) while still operational.

Since FUSE and GALEX, UV observing has generally been combined with other wavelengths. HST's Wide Field Camera 3 is a UV/optical/IR instrument covering a wavelength range from 200 to 1700 nm; *Swift* is a gamma-ray burst telescope (see below) with a small UV/optical telescope (UVOT) intended primarily for observing GRB afterglows, though it has done some stand-alone UV work; Astrosat is an Indian multi-wavelength observatory with a 40 cm UV telescope in addition to several X-ray instruments. Like *Swift,* the X-ray observatory *XMM−Newton* has a small UV/optical telescope (in fact the *Swift* instrument is a copy of XMM's), but this is co-aligned with the X-ray telescope and cannot be used independently.

X-rays

X-ray imaging is much more challenging than UV, basically because it is extremely difficult to get X-rays to reflect (they tend to go through things!). Early X-ray telescopes used collimators to restrict the angle at which X-rays could enter the detector: this works, but produces poor field of view and very limited angular resolution. The modern solution is to use *grazing incidence reflection*, by reflecting off the "sides" of a parabola rather than the "bowl" shape at the bottom. In order to recover the lost surface area, X-ray telescopes usually use several nested parabolae, not just one. As with UV, X-rays are absorbed very high in the atmosphere, and space-based instrumentation is essential for X-ray astronomy. X-rays are traditionally divided into "soft" X-rays, with energies less than about 10 keV ($\lambda > 0.1$ nm) and "hard" X-rays (>10 keV); the boundary between hard x-rays and γ-rays is poorly defined, but usually taken at a few hundred keV.

The first X-ray astronomy missions were sounding rockets and high-altitude balloons. These have limited capability: the balloons do not get high enough to have full coverage, and the sounding rockets can only observe for a short time. However, enough was observed to assure astronomers that X-ray astronomy was a worthwhile study, and the first dedicated orbiting X-ray observatory, *Uhuru*, was launched in 1970 (from Kenya, hence its name, Swahili for "freedom"). *Uhuru* increased the source count tenfold, from 40 to more than 400, identified "X-ray stars" as close binaries with a compact object (neutron star or black hole) accreting from a companion, and discovered the X-ray emitting hot gas in galaxy clusters. *Uhuru* did not have focusing optics: it used collimators to limit its proportional counters to a relatively small field of view (5 and 0.5 degrees square, respectively, for the two sets of counters). It was followed through the 1970s by a series of similar small satellites, built by a variety of countries but all using essentially the same technique.

The first X-ray satellite to use focusing optics with grazing-incidence mirrors was NASA's *Einstein* (1978–81). The improved resolution allowed it to identify more sources and to confirm that most of the previously detected diffuse X-ray background was simply unresolved faint sources. *Einstein*'s catalogue contains over 7000 discrete sources.

Einstein was followed by ESA's EXOSAT (1983–86), with a smaller collecting area and poorer spatial resolution, but good time resolution: it specialised in studies of variability. The next big advance in sensitivity was Germany's ROSAT (1990–99), with around three times *Einstein*'s collecting area. ROSAT's source catalogue includes over 125000 sources. It was a soft X-ray instrument (maximum energy 2.5 keV), and specialised in studying hot gas: stellar coronas and the intracluster medium. Overlapping ROSAT's long active life were two complementary satellites: the Japanese ASCA (1993–2000), designed for spectroscopy, with much poorer spatial resolution than ROSAT but full spectroscopic capability over 0.4–12 keV, and the Rossi X-ray Timing Experiment (RXTE, launched 1995), specialising in time-resolved studies of hard X-rays/soft γ-rays (15–200 keV). Hard x-rays are difficult to focus even with grazing-incidence optics, and RXTE uses the older technique of collimation, producing a 1° square field of view. RXTE had a planned lifetime of 5 years, but is still going, in best IUE tradition.

There are several current X-ray satellites. NASA's *Chandra* and ESA's *XMM–Newton*, both launched in 1999, are complementary: *Chandra* is a high-resolution imager (0.5 arcsec, comparable to good ground-based optical) with a collecting area similar to ROSAT; XMM has poorer resolution (5 arcsec), but a better spectrometer and a larger collecting area (4300 cm^2 compared to 1140 for Chandra). Both cover the full soft X-ray region (0.1–10 keV). Japan's *Suzaku* (2005–2015) had three imaging spectrometers covering the soft X-ray region with 2' spatial resolution, and a non-imaging hard X-ray detector (HXD) covering 10–600 keV. *Suzaku* had a run of bad luck: it was itself a replacement for a mission, ASTRO-E, which was lost when its launch vehicle crashed, and a cooling malfunction killed its main X-ray spectrometer, which needed cryogenics for its detectors. However, the other two soft X-ray instruments functioned successfully, as did the HXD, giving it a unique capacity to combine soft and hard X-ray observations. *Suzaku* was switched off in 2015 after developing communications problems; at that point it had already exceeded its planned 2-year lifetime fivefold. Sadly, its successor, *Hitomi*, suffered catastrophic failure soon after orbit insertion, because of a malfunction in its attitude control system.

Gamma-rays

The γ-ray region of the spectrum is not completely restricted to space-based observations. Very high energy γ-rays shower in the Earth's atmosphere, producing Cherenkov radiation which can be seen from the ground on sufficiently dark nights, and there are several γ-ray telescopes operating around the world, including HESS in Namibia, MAGIC on the Canary Islands, VERITAS in the USA and CANGAROO in Australia. However, the threshold for this method of detection is around 30−100 GeV—a factor of 10^6 higher than the tens-of-keV upper limits of most of the X-ray telescopes discussed above. The intermediate hard X-ray/soft-to-medium γ-ray region still requires space-based instruments.

The first γ-ray satellites were not designed with astronomy in mind. The Vela series of military satellites (launched 1963−1970), despite their apparently astronomical name, were actually intended to detect clandestine nuclear explosions. Instead, they detected gamma-ray flashes which (by comparison of arrival times at different satellites) could not be coming from the surface of the Earth, but must be astronomical. These data were declassified and published in 1973, and γ-ray astronomy was born.

The first astronomical γ-ray satellite was NASA's Compton Gamma-Ray Observatory (CGRO; 1991−2000). CGRO had a range of instruments which together covered the whole hard x-ray/soft γ-ray region, from 30 keV to 30 GeV. The instruments did not have focusing optics, because high energy photons just don't reflect, but some reconstructed incident particle directions in the manner of a small high-energy physics experiment (technically, γ-ray astronomy is much closer to particle physics than it is to ordinary optical astronomy; many γ-ray astronomers trained as particle physicists or cosmic-ray physicists). Their angular resolution ranged from a few degrees to a few arc minutes, depending on the instrument and the energy. This was sufficient to investigate the spatial distribution of sources and to attempt to detect specific objects, e.g. the Crab pulsar, but not sufficient to provide good positions for optical follow-up of unidentified sources such as gamma-ray bursts.

CGRO's BATSE (Burst and Transient Source Explorer) instrument detected hundreds of gamma-ray bursts, which turned out to be distributed very isotropically. This situation was somewhat reminiscent of the early radio source catalogues: either the sources are faint and local (because they were very isotropic, "local" may mean *very* local: the Oort Cloud was suggested), or they are extremely luminous and extragalactic.

This question was resolved by the Dutch-Italian BeppoSAX satellite (1996−2002), which covered the energy range from soft X-rays through to very hard X-rays (0.1-300 keV). Though there were no focusing optics even in the soft X-ray range, one of the soft X-ray instruments had a fair angular resolution of about an arcminute. Since high and low energy instruments point in the same direction, BeppoSAX was able to discover that some gamma-ray bursts have X-ray afterglows, and to locate the first such with sufficient accuracy that optical follow-up measurements were able to detect an optical afterglow and subsequently to identify the host galaxy of the burst. This and subsequent detections confirmed, as with radio sources, that the GRBs were in fact extragalactic.

The High Energy Transient Explorer (HETE-2), launched in 2000, has a similar energy coverage to BeppoSAX and is designed for accurate location of gamma-ray bursts. It was joined in 2004 by *Swift*, which has a UV-optical telescope as well as a gamma-ray detector and an X-ray telescope, and is designed to give very quick multi-wavelength coverage of any GRB, along with good (arcsecond) position resolution for ground-based follow-up. Unlike previous γ-ray-plus-X-ray satellites, *Swift*'s X-ray telescope has focusing optics with 18" resolution; the sub-arcsecond resolution is provided by the UV-optical telescope. Like several previous experiments, the γ-ray imager uses a "coded mask": this is a clever technique that uses shadow patterns from a partially opaque mask to deduce the direction of the source. It is ideal for hard X-rays and soft γ-rays, which are too energetic to reflect even at grazing incidence, but too low in energy to be tracked by particle-physics techniques which rely on pair production, $\gamma \to e^+e^-$.

10.2.2 Long wavelengths

Infrared

Infrared astronomy has several advantages over visible light: infrared penetrates dust more easily, allowing observation of, e.g., the Galactic centre; cool objects such as brown dwarfs, protostars and gas clouds can be studied; and at high redshift, ~1 or more, the "visible" spectrum is actually detected in the infrared. For these reasons, plus the fact that the longer wavelength is more suited to adaptive optics, much ground-based astronomy is now done in the near infrared. However, ground-based infrared astronomy is restricted to a few favourable "windows" where molecular absorption by H_2O and CO_2 happens to be low. All of these are in the near infrared (<4 μm); mid and far infrared observing cannot be done from the ground.

The detection of infrared radiation poses problems because of the low energy of the radiation and the fact that room-temperature objects emit copiously in the infrared. Most infrared detectors therefore need active cooling, which limits the lifetime of satellite observatories. Detectors are usually solid-state devices using unusual semiconductors with small band gaps, or bolometer arrays which measure a temperature rise in a cryogenic target—commonly germanium, whose conductivity is temperature dependent.

In the 1960s and 70s, infrared observing was done from the ground (using the near-infrared windows), or by balloons, sounding rockets and high-altitude aircraft. The first space-based infrared observatory was the InfraRed Astronomical Satellite (IRAS), a UK-US-Netherlands collaboration, launched in 1983. IRAS was a sky survey mission, covering (almost) the entire sky at 12, 25, 60 and 100 μm (mid and far infrared). It was extremely successful, doubling the known source count to around 350,000 catalogued sources and providing data on solar system objects (discovering 6 new comets) and dust, protostars and star formation, the Galactic centre, and around 75,000 strongly star-forming galaxies (starburst galaxies and interacting galaxies). Considering that the satellite's useful life (before running out of coolant) was only 10 months, this is a remarkable achievement.

After IRAS, there was a brief period of coverage when the Space Shuttle's Spacelab mission flew an infrared telescope, but apart from that the next major space-based mission (excluding COBE, see below) was ESA's Infrared Space Observatory (ISO) in 1995. ISO had much the same science goals as IRAS, but had a proper spectrometer instead of a few discrete wavebands, greater sensitivity, and a polarimeter. It covered the wavelength range from 2.5 to 240 μm. It also lasted nearly three times as long as IRAS, from November 1995 to May 1998. The Midcourse

Space Experiment (MSX: I've no idea what "midcourse" is supposed to signify), launched in 1996, was essentially an updated IRAS, with four wavebands at 8, 12, 15 and 21 μm and better spatial resolution: it filled in the gaps in IRAS' sky survey, surveyed the Galactic plane, and conducted targeted surveys of crowded fields (where its improved spatial resolution was of most benefit). HST has also probed the near infrared, with the NICMOS camera/multi-object spectrometer.

Another sky survey instrument was the Wide-field Infrared Survey Explorer (WISE; 2010), which had a 40 cm telescope observing at 3.4, 4.6, 12 and 22 μm (mid-infrared). As its name suggests, this was a sky survey mission, similar to IRAS but a great deal more sensitive. After exhausting its coolant, WISE continued operation in its lowest-wavelength bands (least affected by thermal background) as a dedicated search for minor solar system bodies (comets and asteroids). After being put into hibernation in early 2011, WISE was reactivated in 2013 to take part in NASA's dedicated search for potentially hazardous near-Earth asteroids.

The two major infrared telescopes of recent years were the Spitzer Space Telescope (cold mission 2003–2009; warm mission ongoing) and the Herschel Space Observatory (2009–2013). To reduce cooling requirements, neither *Spitzer* nor *Herschel* was placed in Earth orbit, since the Earth is an intense source of infrared. *Spitzer* was launched into an Earth-trailing heliocentric orbit: it has a slightly longer orbital period than the Earth, so gradually falls behind over the course of its projected several-year lifetime. *Herschel*, which was launched along with the *Planck* cosmic background mission, was located at the L2 Lagrange point, 1.5 million kilometres out along the Sun-Earth line.

Spitzer carries four instruments, the InfraRed Array Camera (IRAC) operating at 3.6, 4.5, 5.8 and 8 μm, the InfraRed Spectrgraph IRS covering 5.3–37 μm, and the Multiband Imaging Photometer for Spitzer (MIPS) covering 24, 70 and 160 μm. During the cold mission, it therefore spanned almost the entire wavelength range covered by all its predecessors, though since the exhaustion of its helium coolant only the 3.6 and 4.5 μm passbands of IRAC are still usable. It has an 85 cm diameter telescope, considerably smaller than HST's 2.4 m, but bigger than either IRAS or ISO (both 60 cm). The main advantage of *Spitzer* over IRAS and ISO is not the absolute mirror size, but the improvements in infrared detection technology which had taken place in the intervening years.

Herschel (2009–2013) was much the largest infrared telescope ever launched, with a 3.5 m mirror (double the collecting area of the HST). It was a far infrared and submillimetre observatory, with two low-resolution imaging spectrometers (PACS and SPIRE) covering the wavelength range 55–672 μm and a non-imaging high-resolution spectrometer covering 157–212 and 240–625 μm. As a far-infrared instrument, *Herschel* was entirely dependent on cryogenic detectors, and ceased operation when its liquid helium coolant was exhausted.

CMB

The long wavelength side of the cosmic microwave background spectrum was established by 1968, as discussed in the last chapter. However, a 2.7 K blackbody spectrum peaks at about 1 mm, which is not accessible to ground-based observations, and so it proved very difficult to establish the exact shape of the peak region satisfactorily. Balloon and rocket-based observations, and indirect determinations using interstellar molecular absorption[1] had provided

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[1] Interestingly, the first such absorption measurement actually predates Alpher and Herman's prediction by several years: it was made by Adams and McKellar in 1941, based on CH and CN molecular lines observed by Adams and interpreted by McKellar. They obtained the "correct" value of 2–3 K. It is curious that nobody in 1950 put this together with Alpher and Herman's prediction. Probably the McKellar and

some information, but there was disagreement: Woody and Richards (1981) reported that their balloon results were not consistent with a pure blackbody spectrum, whereas Meyer and Jura (1985) stated that their results from CN absorption did fit a blackbody. This was vital information, since a non-blackbody background is not inconsistent with alternative cosmological models, whereas a pure blackbody is extremely difficult to explain without a hot, dense phase in the history of the universe.

The COsmic Background Explorer (COBE) satellite, launched in 1989, was designed to resolve this question, and to look for the small anisotropies in the radiation which were required to act as seeds of later structure formation (recall that the CMB corresponds to a redshift of 1100 and was emitted only 400,000 years after the Big Bang). Although its angular resolution was only adequate to map the very largest anisotropies (and, with amplitudes of only 10^{-5}, they turned out to be at the very limit of its sensitivity), it was successful in both objectives, and subsequently earned its leading scientists, **John Mather** (b. 1946) and **George Smoot** (b. 1945) the 2006 Nobel Prize for Physics. COBE carried far-infrared instrumentation (the Far InfraRed Absolute Spectrometer, FIRAS, 0.1–10 mm, and the Diffuse InfraRed Background Experiment, DIRBE, 1–300 μm) and microwave radiometers working at wavelengths of 3.3, 5.7, 9.5 and 16 mm. Appropriately, the radiometers were Dicke radiometers, based on the original Princeton design. The three sets of instrumentation were designed to measure the blackbody spectrum (FIRAS), to look for anisotropies (the microwave radiometers) and to study the scattered-starlight infrared background (DIRBE).

The discovery of anisotropies was followed up by several ground-based instruments (wavelengths of a few millimetres are observable from good ground-based sites) before the launch of the Wilkinson Microwave Anisotropy Probe (WMAP; it originally had the elegant and appropriate acronym of MAP, but the W was added to commemorate David Wilkinson, near-discoverer of the CMB and one of MAP's principal scientists, who died in 2002) in 2001. Even more than *Spitzer*, WMAP relied on passive cooling, and therefore (unlike COBE) would not work in Earth orbit: like *Herschel*, it was placed orbit around the L2 equilibrium point of the Earth-Sun system, 1.5 million kilometres anti-Sunward of the Earth (at this point, the Earth's gravity added to the Sun's results in an orbital period which exactly matches the Earth's, so the Sun-Earth-L2 line remains straight). WMAP operated from 2001 to 2010 (it was switched off following the arrival of *Planck*) and was extremely successful, measuring many cosmological parameters with unprecedented accuracy. It made observations at five microwave frequencies, 22, 30, 40, 60 and 90 GHz, corresponding to wavelengths of 14, 10, 7.5, 5.0 and 3.3 mm respectively, with an angular resolution ranging from 0.93° at the lowest frequency to 0.23° at the highest. (This should be compared to about 7° for COBE.)

WMAP was succeeded by the ESA CMB mapper *Planck* (2009–2013), which had better angular resolution and greater sensitivity to polarisation. *Planck* carried two instruments, one specialising in low frequencies (30, 44 and 70 GHz, corresponding to 10, 6.8 and 4.3 mm) and the other high (100, 143, 217, 353, 545 and 857 GHz; 3.0, 2.1, 1.4, 0.85, 0.55 and 0.35 mm), with angular resolutions between 0.55° and 0.083°: though its principal target was the CMB, it could also do far-infrared astronomy, and has released two catalogues of compact sources. While WMAP relied entirely on passive cooling, and therefore had an essentially indefinite lifetime, *Planck*'s use of higher frequencies made it more susceptible to background noise, and it needed active cooling. It was decommissioned in 2013 following the exhaustion of its liquid helium coolant.

Adams result was interpreted at the time as scattered starlight (which has an effective temperature of around 3 K, but is not a blackbody) as predicted by Eddington.

10.2.3 Summary

Exploring the previously inaccessible regions of the electromagnetic spectrum has been extremely productive. These missions have produced a large number of new and unexpected discoveries: gamma-ray bursts, the hot X-ray emitting gas in rich clusters, the extremely luminous infrared galaxies, etc. They have also offered revealing insights into previously known phenomena: for example, X-ray observations probe conditions close to the event horizon of accreting black holes, and thus complement the radio and visual observations which relate to regions further out; infrared observations penetrate dust, and hence can provide data on deeply enshrouded objects such as protostellar cores and the Galactic centre, as well as studying genuinely cool objects such as brown dwarfs and molecular clouds which emit most of their radiation in the infrared. Cosmic microwave background observations, which combine ground-based and space-based instrumentation, have introduced an era of "precision cosmology" which was unimaginable 25 years ago. Whole subfields of astronomy which did not exist prior to the 1970s have been opened up by space-based observation, and it is now essentially unthinkable to restrict observations of interesting astrophysical phenomena to just those wavebands which can be observed from the ground.

10.3 Precision Observations

Even in the optical window, the atmosphere has a deleterious effect on image quality. Before the recent development of adaptive optics, the best resolution that could be expected (and then only at an outstanding site in perfect conditions) was ~0.5" (about the diffraction limit of a 23-cm objective). This causes many problems, not all of them self-evident:

- fine structure (angular size <0.5") is extremely difficult to observe (it may be possible to detect fine structure by deconvolution methods, but there is a limit to how much information can be retrieved);
- objects in crowded fields, e.g. a Cepheid in the spiral arm of a fairly nearby galaxy, cannot be accurately measured because each pixel of the field contains light from multiple sources;
- faint objects cannot be detected because their light is not concentrated in a single pixel;
- position measurement is compromised by the need to fit the "point spread function" of the light;
- scattered light creates a non-zero background "sky brightness" which makes it difficult to measure faint extended objects (a slight error in the sky brightness subtraction may have large implications for the measured size of a faint galaxy, for example).

These problems can clearly be overcome by situating a telescope beyond the atmosphere. As long ago as 1923, **Hermann Oberth**, one of the pioneers of German rocket science, suggested putting a telescope in orbit; the American astronomer **Lyman Spitzer Jr** wrote a paper on the subject in 1946, when the idea had become slightly less far-fetched, and NASA provisionally approved a space telescope project in 1969. After the usual downsizing to meet budget constraints, funding was approved in 1977, and construction completed in 1985. Owing to the Challenger disaster, the HST was not actually launched until 1990; as a consequence of the well-known problem with the figure of the primary mirror, the first data with design resolution were not taken until 1993, after the COSTAR correcting optics were fitted.

Since then, the HST has of course delivered an extremely productive science programme. Unlike the missions described in the previous section, which probe wavelengths inaccessible from the ground, HST is *not* primarily a "discovery machine" (despite what NASA publicity may say!):

very few real discoveries can be credited to HST. Instead, HST provides unparalleled precision and detail: it is a perfect follow-up machine to turn hints from ground-based or non-optical instruments into concrete science. The areas in which HST makes its greatest contributions are precisely those highlighted above as presenting challenges to ground-based observations: crowded fields (e.g. the measurement of Cepheids in Virgo cluster galaxies, fundamental to the Key Project work on determining H_0), fine structure (e.g. in planetary nebulae, around active galactic nuclei, etc.), and faint objects (particularly the various Hubble Deep Fields, but also in resolving quasar host galaxies and measuring the spectra of distant Type Ia supernovae). During the periods of operation of the NICMOS near infrared spectrometer (1997−99 and 2002−2008), it also had the distinction of being much the largest orbiting infrared telescope (until *Herschel*), though it never had the long wavelength capabilities of *Herschel* and *Spitzer*. The HST has become indispensable to astronomers: a study published in 2010[2] recorded a steady 600 or so papers per year based on HST data. A critical point is that HST data become open access one year after the observations were made, so that other astronomers can then use the data to support what may be entirely unrelated research programmes (e.g. searching for supernova progenitors): about half the 600 papers are based on such archival data.

The other area mentioned above as a problem for ground-based instrumentation is the precision measurement of position. This has not been a priority of HST, understandably—it is a heavily oversubscribed facility and must choose projects with the highest scientific return. However, it was the focus of a much smaller, dedicated instrument, HIPPARCOS (the HIgh Precision PARallax COllecting Satellite). This ESA mission (1989−93) had a small telescope (29 cm diameter) with optics designed to view two widely separated fields simultaneously, thus providing accurate relative positions which could later be analysed to yield parallaxes.

The satellite was designed to operate in a geostationary orbit with permanent contact with its ground station, like IUE; unfortunately, its booster failed to operate and it actually entered a highly elliptical orbit with apogee at geostationary but perigee only 500 km up. This both placed it out of sight of its ground station for much of its orbit (which had a period of 10 hours rather than the intended 24) and exposed its solar panels to the Earth's van Allen belts twice an orbit, with potential for severe radiation damage. However, it proved possible to recruit two more ground stations to receive data, and by good luck the solar panels were more radiation resistant than had been feared: in the end, the satellite achieved all its original mission goals. The final results included two star catalogues, the Hipparcos catalogue containing around 120,000 stars with parallaxes measured to 1 mas (milli-arcsecond) accuracy, and the Tycho-2 catalogue containing around two million stars with ±20-30 mas parallaxes, photometry and proper motions. Although a few issues have arisen, most notably with the parallax of the Pleiades (which is certainly slightly wrong), the *Hipparcos* mission was a great success. A follow-up astrometry satellite, *Gaia*, with a larger telescope which will allow the observation of a much larger sample of stars, launched in 2013, and its first data release is planned for 2016. *Gaia* is expected to measure the distances of 20 million stars to a precision of 1%, and about 10 times as many with 10% precision. Unlike *Hipparcos*, *Gaia* carries additional instruments besides the parallax telescope: a photometric instrument providing colour information, and—crucially—a radial velocity spectrometer (RVS) to measure line-of-sight velocities by Doppler shift. Any parallax-measuring instrument measures proper motion (motion transverse to the line of sight, usually expressed in arcseconds per year), but the addition of the RVS will allow *Gaia* to provide full three-dimensional velocity vectors, which will allow astronomers to model the dynamics of the Milky Way.

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[2] Jill Lagerstrom, contribution to the 76th IFLA General Conference, August 2010

Summary

Space-based observing at optical wavelengths benefits from increased precision and resolution. This confers many advantages in observing faint sources, crowded fields and fine structure, and in making high-precision positional measurements such as parallaxes. The HST has become an indispensable tool for many observational astronomers, and the anticipated *Gaia* catalogue of around a billion stars will doubtless be equally valuable for a user community ranging from solar system astronomers (*Gaia* will be an excellent tool for discovering minor bodies) to cosmologists (solidifying the foundations of the distance scale, using Galactic dynamics to investigate the distribution of dark matter, studying gravitational microlensing events) and even some fundamental physics, e.g. looking for variation in G.

10.4 The impact of space-based instrumentation

The astronomical space age is only about 50 years old, so arguably it does not belong to "history" at all. On the other hand, very few working astronomers remember the pre-space era of astronomy, and its impact on all branches of the field is undeniable.

Space-based instrumentation provides many disparate examples of discovery and progress in astronomy and astrophysics. In many cases, the opening up of a new wavelength range has yielded entirely unexpected phenomena, such as gamma-ray bursts and luminous infrared galaxies. Other fields have been revolutionised by access to new wavelengths: although active galactic nuclei were discovered by ground-based radio telescopes, modern studies rely heavily on X-ray observations, and the same is true for other non-thermal sources such as supernova remnants. Meanwhile, the HST has provided not only unparalleled resolution, but also, through the Deep Fields, images of extremely faint objects (not because it has a particularly large telescope—it doesn't—but because it can make extremely long exposures (and CCDs do not suffer from reciprocity failure, so an image with ten times the exposure has ten times the sensitivity). Overall, the impact of space-based observatories can be likened to the impact of the telescope in terms of its effect on our understanding of astronomical phenomena.

Meanwhile, the physical exploration of the solar system by spacecraft has had a similarly profound effect on our understanding of the physical properties of the planets and minor bodies of our solar system. Although much can be done by space-based observatories, there is no real substitute for close contact: even a flyby mission such as *New Horizons* provides far better resolution than an Earth-based telescope. In the case of planetary astronomy, the field has been further, and perhaps more dramatically, shaken up by the wealth of information on extrasolar planets obtained over the past two decades. Here, too, space-based astronomy has proven its worth, with more than half of all extrasolar planets discovered by the *Kepler* transit search—an application of the high precision available in the absence of the atmosphere.

Without space-based instrumentation, modern astronomy would be unrecognisable. Many entire fields, such as X-ray astronomy, would not exist; many entire classes of object, such as gamma-ray bursts, would never have been discovered. This is another example of an area in which astronomy is not the oldest but one of the youngest sciences: while an astronomer from 1900 would have felt reasonably at home in the observational astronomy of the 1950s (though completely astonished by the theoretical side) an astronomer of the 1950s would find the exact opposite: the theory, though much advanced, would be comprehensible, but the observational side would seem like science fiction.