Techniques of Modern Observational Astrophysics

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Abstract

Observational astronomy has advanced to the point where nearly all of the electromagnetic spectrum is covered with very high sensitivity. This paper will discuss the methods used for observing at various wavelengths, focusing on the similarities between the instrument and telescope designs in the optical and high energy regions. It will also describe some of the observed sources and the necessity of using specific techniques to find such sources. A description of the Earth's atmosphere and its effects on observation is included as it is the driving factor behind some of the described techniques, including adaptive optics, space-based telescopes and optical interferometry. New techniques continually extend the limit of our understanding about the universe and there will be no shortage of surprises for years to come.

Contents

1 Introduction

From the days of antiquity, humankind has attempted to understand the heavens. In the past century, our understanding has drastically increased due to the use of novel techniques and observations across the electromagnetic spectrum. In the past fifteen years, there has been a steady stream of new discoveries stemming from highly advanced observing techniques, especially in extreme wavelengths. This paper will describe some of most recent observatories and the techniques employed to confront the problems associated with observations at different wavelengths. The focus will be on the techniques which apply to multiple wavelength bands with particular attention to the optical and high-energy regions.

Astronomy is one of the few domains of physics in which experiments cannot be directly performed. Though it is possible to perform laboratory simulations and computer models of phenomena, it is not possible to go directly to the source and take samples. Observational astronomy takes the role of experiment and observations at multiple wavelengths garner more information about the sources of radiation. Modern observational astronomy makes use of an incredible extent of energies, ranging from km length radio waves to cosmic rays with energies of over a Joule per particle. This range includes over eighteen orders of magnitude and wildly different techniques are required for different spectral regions. A significant fraction of the current state of the art instruments are orbital observatories, as the wavelengths which they investigate are invisible to ground-based observers. For ground-based observatories, it has become necessary to actively account for atmospheric effects which I will also cover in some detail.

I will use the following distinctions between wavebands (listed here by wavelength) for this discussion: radio from kilometer to millimeter, infrared (IR) from millimeter to 900nm, optical/visual from 900nm to 300nm, ultraviolet (UV) from 300nm to 10nm, X-ray from 10nm to 10pm, and gamma-ray for all wavelengths below this. However, these wavebands are not always referred to by wavelength: X-rays are commonly separated by energy and the radio spectrum is more often described by frequency. Thus X-rays would run from roughly 0.2keV to 100keV. These distinctions are rather arbitrary, however. For instance the soft X-rays—under 1keV—bleed into the extreme UV and observing techniques used in one band will often carry over.

For many years, the visual spectrum was all that astronomers could use for observation. Though Karl Jansky began initial observations in the radio spectrum in 1931, no other wavelengths were available for many years due to the effects of our atmosphere. Even after rockets and satellites were able to pass above our atmosphere, there was a suspicion that there would be no sources visible at very short wavelengths due to interstellar absorption and the temperatures associated with these wavelengths. The latter thought stemmed from the standard model of photon production, blackbody (thermal) radiation. Higher photon energies are generally associated with higher temperatures in the source object. Assuming an object is a blackbody with its peak wavelength in soft x-rays (around 1nm) and applying Wien's law [1, pg 532],

$$T * \lambda_{max} = 2.898 * 10^{-3}\text{m} \cdot \text{K}, \tag{1.1.0.1}$$

where T is the temperature in Kelvin and λ_{max} is the maximum wavelength emitted in meters, this object would have a temperature of nearly 3 million Kelvin! Though the solar corona was suspected to have similar temperatures, it is not very luminous. In fact, the sun is so dim in X-rays that instruments available in the 1960s would be capable of observing objects 1 kiloparsec (roughly 3000 light years) away only if they had over 100 billion times the X-ray luminosity of the sun [2, pg 2]. Thus, the prevailing opinion of most observers during this period was that there would be very few interesting objects to observe in high energies. The serendipitous discovery of the X-ray source Sco X-1 in 1962 [2, pg 2] suggested that other photon production methods besides thermal radiation must exist. Since then numerous other sources producing such radiation have been found, though our ability to observe them is limited by our atmosphere.

2 Earth's atmosphere

That we live on a planet surrounded by a significant atmosphere is good for our survival, but a hindrance for astronomers. When one looks at the stars at night, it is often possible to see flickering among the bright stars while dimmer stars may fade in and out of view. When viewing a star, planet, or other bright object through an optical telescope this wavering is much more apparent and is referred to as "seeing." This seeing is the most obvious effect of our atmosphere on observational astronomy but is definitely not the only problem. The atmosphere, composed mostly of nitrogen, oxygen and carbon dioxide, absorbs many wavelengths which would otherwise be highly useful for observation. There is also the effect of atomic emission, which though most visible during northern lights displays, always occurs to some degree. Attenuation and refraction of light is one of the greatest limiting factors of ground-based observing, as light from distant objects is altered, causing even a powerful telescope like Keck I/II to be more limited by atmospheric effects than by mechanical errors or inherent limitations.[1]

Earth's atmosphere ranges from ground level to beyond 100km and each level reduces our ability to observe different regions of the spectrum. The displayed curve (Figure 1) is a plot of the temperature gradient of the atmosphere versus increasing elevation (and thus decreasing pressure). The names given to the various levels are those accepted by the World Meteorological Organization and I will refer to them in the discussion that follows.

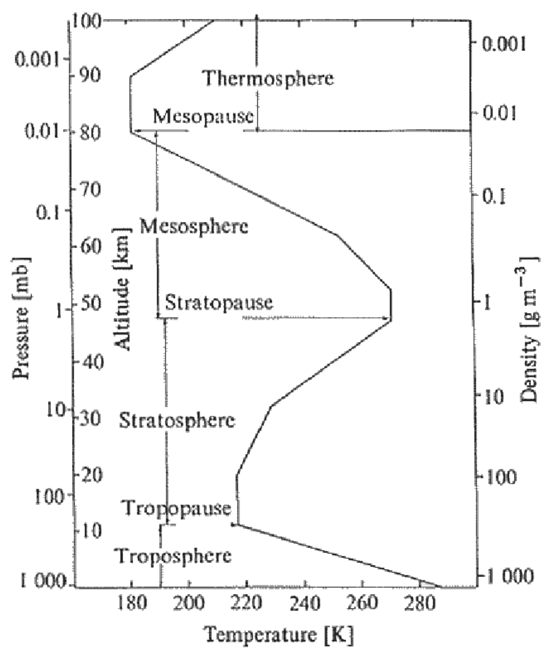

Figure 1: Mean temperature, density and pressure structure of the atmosphere, from ground level to 100km. The names of the various levels are those accepted by the World Meteorological Organization [3, pg 32].

2.1 Atmospheric absorption and emission

The two most basic problems that our atmosphere causes for observation are absorption of incoming radiation and emission, both fluorescent and thermal. Atomic and molecular transitions cause discrete absorption bands which may be strong enough to completely prevent observation in that spectral region. Fluorescence, also known as airglow, is caused by the recombination of electrons and ions and occurs mostly above 100km. The atmosphere also produces a sizeable quantity of radiation in the infrared

[1] All telescopes have a basic limit to their resolving power. This is termed the diffraction limit and is discussed in more detail in section 4.3.

which can be described by a blackbody spectrum.

Atmospheric absorption occurs as light ionizes atoms and excites atoms and molecules. Particular wavelengths will be absorbed with certain probabilities based on the amount of the substance in the air and the probability of a specific transition. The displayed spectrum of the star γ Cas (Figure 2) shows how overwhelming the atmospheric absorption bands can be. The blackbody curve for the star is readily visible, though there are large gaps due to the absorption from atmospheric water, carbon dioxide and oxygen. There is also no useful data below 4000cm^{-1} due to total atmospheric absorption in that region. With a knowledge of the atmospheric profile at a particular observatory it is possible to computationally correct these affected bands when the absorption is not overwhelming. For instance, the spectrum of a known star can be used to determine relative fluxes, as was done for the upper-right inset in the figure. The spectrum of γ Cas was divided by that of the star α Leo to to determine the relative flux of the Paschen α line, which is otherwise lost within the large water absorption band around 5300cm^{-1}.

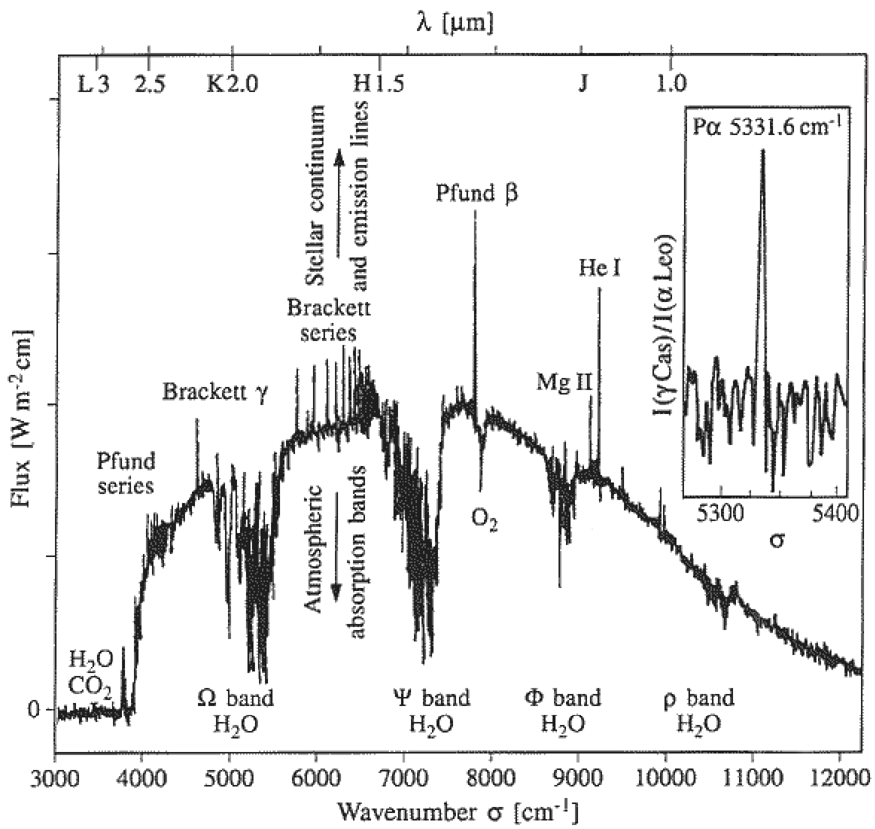

Figure 2: Spectrum of the star γ Cas in the near infrared (centered around 1300nm). The large atmospheric absorption bands are labeled (H_2O, O_2, CO_2). The lower x-axis is given in 1/wavelength. The inset is the relative flux of the Paschen α (1.875μm) line compared to the star α Leo [3, pg 39].

There are some wavelengths which are impossible to observe on the ground. All wavelengths shorter than 300nm and much of the infrared region are completely blocked. The atmospheric absorption profile (Figure 3), gives the minimum height necessary to observe 1, 10 and 50 percent of the incident flux from a source at a given wavelength. The high energy absorption is caused by a combination of excitations and ionizations of molecular oxygen, nitrogen and ozone. This absorption becomes complete molecular ionization for all wavelengths shorter than 10nm, though total photon extinction begins around 200nm. Thus, only after the advent of space-flight has it been possible to make observations at UV, X-ray and gamma-ray wavelengths. On the other hand, the IR absorption curve is produced primarily by the rotational bands of atmospheric water vapor and carbon dioxide. There are some gaps where this IR absorption is less overwhelming. Dry, high-altitude sites make use of these gaps for longer wavelength observations. Finally, the ionospheric plasma reflects some radio wavelengths. Its effect is negligible below centimeter wavelengths, though total reflection occurs above 23.5 m.

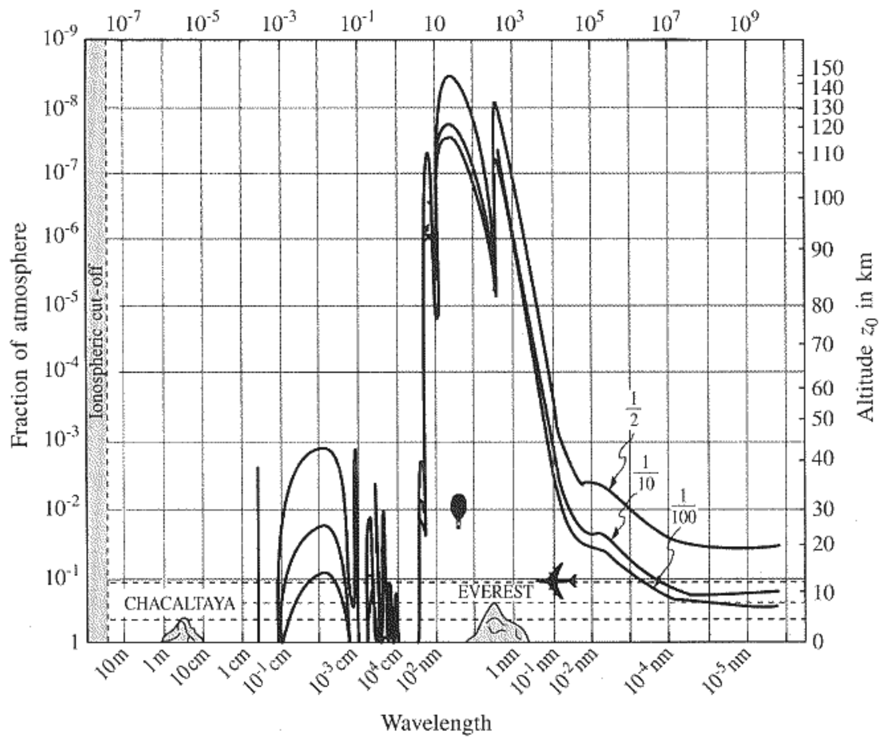

Figure 3: Attenuation of electromagnetic radiation by the atmosphere. The three curves (from bottom to top) are for 1, 10 and 50 percent relative signal strength. The left-hand cut-off is at λ=23m and is caused by ionospheric plasma [3, pg 37].

Atmospheric emission is most prevalent at infrared wavelengths, due to the temperature of the air. Emission in the optical band also occurs and is caused by atomic transitions in the upper atmosphere. This emission can be easily observed by viewing a diffuse source through a filter which blocks light from the 557nm oxygen transition. The Hubble Space Telescope (HST) has been able to observe and catalog several such bands by observing the earth at night and has allowed a calculation of the intrinsic magnitude of the sky [3, pg 44]. Below the stratopause (Figure 1) the atmosphere can be considered as a gas in local thermodynamic equilibrium and it is nearly opaque to IR radiation in this region. One can thus assume blackbody radiation, so taking the mean temperature of this region to be 250K, (eq 1.1.0.1) we find a maximum luminosity of 11μm, in the near IR. This wavelength estimate fluctuates wildly in time, altitude and position on the earth and is strongly affected by the amount of water vapor at a site. For IR observations, this emission poses a limit to the lowest viewable magnitude as the sky will be brighter than the dimmest objects. All of these considerations must be taken into account for ground-based observation at infrared and millimeter wavelengths.

2.2 Other effects

Absorption and Emission are not the only problems our atmosphere causes for ground-based astronomers. The atmosphere also scatters and distorts the light from its original path. The daytime sky is blue due to the Rayleigh scattering of sunlight via air molecules and atmospheric dust. This scattering is very chromatic and affects visible and UV wavelengths the strongest.[2]

The atmosphere is not a stable object and the temperature and density fluctuations cause an effect called "seeing" which is what causes stars to twinkle. Seeing is characterized by the minimum distinguishable angle, given in units of seconds of arc. The largest effects are within the troposphere and lower stratosphere [4, pg 89] and higher elevation sites—Mauna Kea (Hawaii), Cerro Paranal (Chile), Mount Lemmon (Arizona)—have much better seeing due to their being above much of the atmosphere. Typical seeing for such a good site is on the order of 1.0arcsec, though Mauna Kea often has seeing conditions of nearly 0.5arcsec [5].

Artificial interference is becoming more and more of a problem for astronomers, due to the greater spread of technology and the size of cities. In the visual wavelengths, light pollution is beginning to affect sites due to the increased airglow and background radiation. A striking example of this is (Figure 4) where some regions are completely covered in artificial glow. In the infrared, large cities are major sources of thermal disturbance while power plants and industrial facilities produce aerosols which modify the local climate. Radio frequency interference is becoming more and more troublesome due to increased mobile phone and wireless broadband communication use. Currently there are radio frequencies dedicated for astronomical purposes but often rogue radio transmitters use these bands and the high powered signals from radio and television stations often bleed over into protected bands.

[2] Radio waves are unaffected in this way so it is possible to carry out observations in radio at all times of the day, through nearly all conditions.

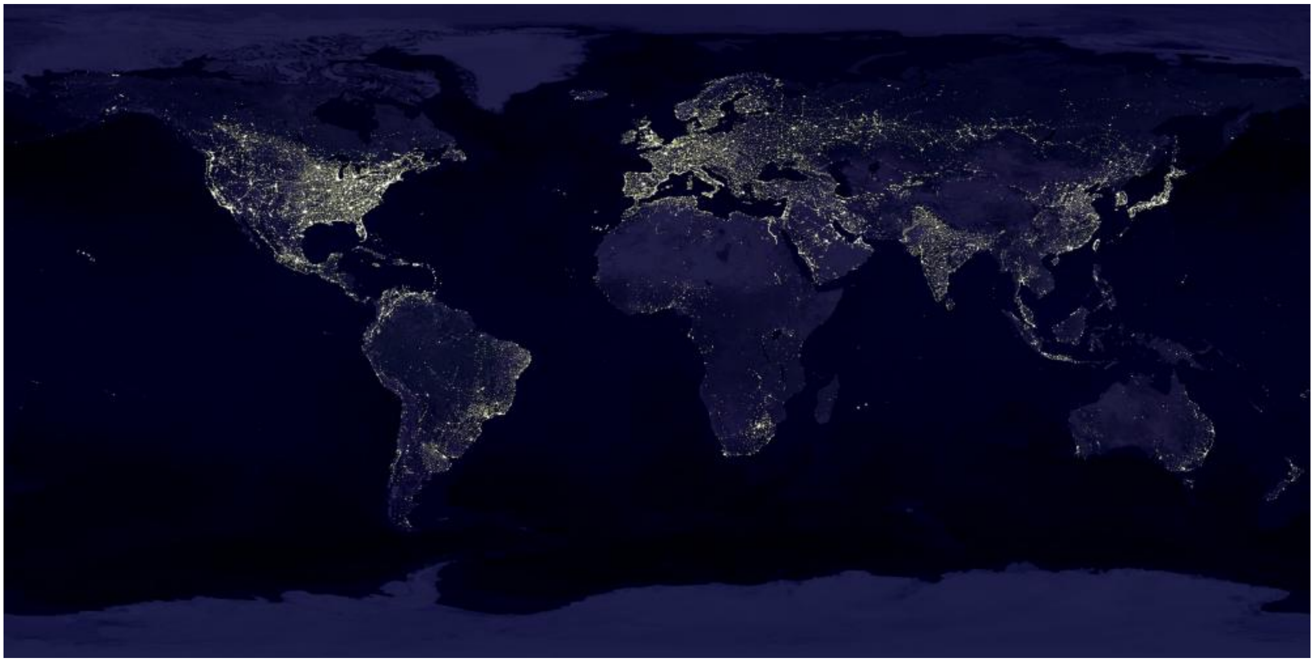

Figure 4: The Earth from space at night. This is a composition of images from the Defense Meteorological Satellite Program compiled by NASA. Urban centers and transportation routes (the USA interstate system, Trans-Siberian railroad, Nile river) are immediately visible.

3 Detection systems

Another important aspect of observational astronomy are the detectors. A powerful telescope at a site with good seeing will not be effective unless it is coupled with a high quality detection system. Thus, I will now describe some of the detectors that are currently being used in observational astronomy. The basic physical principles behind these detectors include photoionization of a gas or solid, the photoelectric effect, photoconduction and direct detection of the electromagnetic field for 0.2mm and longer wavelengths.[3] At high energies, proportional counters such are used to count single photon hits with very good energy resolution. The most ubiquitous detector for the visual wavelengths is the charge-coupled device (CCD). Photographic plates were in use for many years, but have been almost entirely replaced with CCDs. At long wavelengths there is not yet a system for detecting single photons but the electromagnetic field itself can be directly detected by the current it induces in an antenna. As I do not have space to describe radio detectors, a good description of their theory and design can be found in [3, pg 309].

[3] For a review of the theory behind the photoelectric effect, please refer to appendix A.

3.1 Proportional counters

Proportional counters make use of the ionization properties of higher energy photons. When a photon with a high enough energy passes through a gas, atoms within the gas may be ionized. In the most basic proportional counter, the electrons which are freed in this reaction are accelerated through a potential difference to a wire, causing even more ionizations as they move. This results in a large cascade of electrons at the location of the wire, with the detected charge proportional to the energy of the incident photon. This relation is purely linear up to some maximum energy—usually around 10keV—which causes the tube to short. Noble gases such as argon are often used due to their high gain and lack of non-ionization excitation methods [3, pg 304].

3.2 CCDs

The current method of recording visible wavelength images is the use of specialized digital cameras of very high sensitivity called CCDs. CCDs are very powerful tools, as their wavelength response is essentially linear, their photon sensitivity is very high and they have very good pixel uniformity. They are used for observations from the infrared through soft X-rays with design differences being essentially limited to different doping substances and pixel thicknesses to adjust the sensitivity at specific wavelengths.

CCDs are used in the currently popular digital cameras, though those used for astronomy have a much greater sensitivity and more stable wavelength response. Each pixel on the CCD will respond to incident light by releasing electrons via photoconduction (see appendix A). These photoelectrons are collected in a quantum well and are read out after the exposure is completed, giving a total charge proportional to the amount of incident light. Most visible and shorter wavelength CCDs are composed of p-type silicon semiconductors while infrared CCDs more often use germanium or indium antinomide because of their longer threshold wavelength. The most sensitive CCDs can count single photon hits, but these typically are only for higher energy photons. CCDs in the optical region have a quantum sensitivity of better than 90% [3, pg 331], but even the best CCD is not as sensitive as a photomultiplier tube (PMT), such as is used in high energy particle physics. The CCD response time is also slower that that of a so they are not ideal for high speed imaging—millisecond pulsars for instance. However, it is possible to combine multiple CCDs into an array with a very large number of pixels, allowing very wide field views to be taken. In this manner, the HST Wide Field and Planetary Camera-2 (WFPC-2) has taken images of very large sources and has been used for galactic surveys on very large scales. The Hubble Deep Field (HDF) is an example of this, where an fairly empty region of sky with about 2.5 arcmin diameter was imaged for ten days, resulting in a large sample of galaxies stretching back to the very early universe.

4 The visible region (300nm-900nm)

I will begin my discussion of techniques in the various spectral regions with the visible region, as it is the part of the spectrum we deal with the most. By the term visible I am referring to the region from 300nm (near ultraviolet) to 1000nm (near infrared), as basic telescope design in this entire region stems from the theory of geometrical optics. Also, it is possible to use all of this band as the atmosphere is not opaque to it. Though the theory has been refined somewhat and the exact implementation varies between telescopes, Fermat's principle of least time is the guiding principle from which most discussions of optics descend. In most modern systems, multiple mirrors are used, where the secondary or ternary mirrors correct some of the aberrations of the primary. One of the most promising modern techniques is that of optical interferometry, where the light from multiple telescopes is combined to produce an image with resolution equal to the spacing between the telescopes. All modern optical observations from infrared through hard X-rays are performed with charge-coupled devices (CCDs) which have very high sensitivity and as they are digital, allow instant manipulation of images via a computer.

4.1 Telescope design

4.1.1 Geometrical optics

A basic analytical technique in geometrical optics, which I will employ, uses Fermat's principle. Stated simply, Fermat's principle is that the path a light ray follows between two points on a single plane surface is that for which the minimum optical path length is required [6, pg 22]. This statement is fine for a single reflecting or refracting surface, but must be modified somewhat for multiple surfaces. For a single surface such as (Figure 5), the statement is that the optical path length, τ, for a ray of light from P to Q is stationary with respect to infinitesimal changes in the path. Thus, if the ray intersects the surface at some point (x, y) we have

$$\partial\tau/\partial x = \partial\tau/\partial y = 0. \tag{4.4.1.1}$$

For a multi-mirror system, we then have the modern general statement of Fermat's principle, where c is the speed of light in a vacuum and v is the speed of light in a medium of index n [6, pg 23]

$$d\tau = c\,dt = (c/v)\,v\,dt = n\,ds \quad \Rightarrow \tau = c\int dt = \int n\,ds. \tag{4.4.1.2}$$

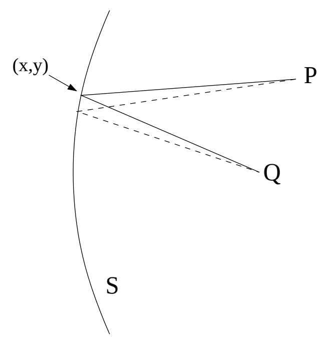

Figure 5: Path of a light ray reflecting off a surface S. According to Fermat's principle, changing (x, y) slightly will not change the optical path length from P to Q.

From this it is possible to derive the optimal shape to bring incident on-axis plane waves to focus at a point

$$y = \frac{x^2}{4F}. \tag{4.4.1.3}$$

This results in a paraboloidal surface, with its focus at $y = F$. This is the mirror surface which most current telescopes employ regardless of wavelength. It is not the most ideal shape for all situations however and it suffers strongly when the incident light is not parallel to the axis.

All four conics can be used to focus light and each has its own advantages and disadvantages. Looking at a vertically oriented hemisphere of radius r with its edge on the axis, we have

$$y = r + \sqrt{r^2 - x^2}. \tag{4.4.1.4}$$

If we expand this as a power series in x/r, we find

$$y = \frac{x^2}{2r} + \frac{x^4}{8r^3} + \frac{x^6}{16r^5} + \dots , \tag{4.4.1.5}$$

the first term of which is that of a parabola with focus $F = r/2$ [7, pg 158]. Thus one can approximate a sphere as a parabola to first order, with the remaining terms describing the perturbations from parabolic. It is possible to use higher order polynomials to correct for some of the aberrations inherent in either of these designs. This is the manner in which the latest X-ray telescopes are designed, beginning with the above equation and altering the coefficients to produce the desired shape.

4.1.2 The five primary aberrations

The above analysis assumed that all sources were at infinity and parallel to the axis of the mirror. Correcting for these assumptions leads us to five primary aberrations. These are spherical aberration, coma, astigmatism, field curvature and distortion [6]. Different mirror and focus combinations are used to correct for each type, but no system is perfect. Thus, at the Cassegrain focus of a telescope[4], the image will have no spherical aberrations but coma and astigmatism become important.

The first aberration I will discuss is spherical aberration. For a spherical mirror, the focus is not at one point, but rather on a line, due to the deviation from a parabola as described above. Parabolic mirrors are not affected at all by this problem. For some systems, this is not a problem as the detection system can be designed to compensate. Spherical aberration is what affected the HST and required corrective optics to be installed in 1994. The HST primary mirror was milled 2μm too shallow and so the focus became spread out.

Whereas spherical aberration is most obvious in a spherical mirror, coma becomes most apparent in a paraboloidal mirror. For a parabola, any ray striking the mirror from off-axis will not be sent to the focal point. Coma does not affect a spherical mirror at all, since there is no axis to the mirror, whereas the analysis of a paraboloidal mirror requires one.

Astigmatism is produced when the surface curvature is non-spherical or not the same curvature in two planes. The effect is that point sources are distended and focusing becomes very difficult. It can be readily corrected for with secondary optics.

[4]For more information, see section 4.1.3.

When the focus of a mirror is not a single point or plane but rather a curved surface, field curvature results. This aberration affects spherical mirrors and high-order polynomial systems. The effects are similar to distortion, but can be corrected by making the detection system curved to match the focal plane. Thus, some multi-CCD arrays are curved in shape, to help correct for this effect.

A mirror producing distortion will cause the images of objects to have incorrect spacing. This is a very dangerous aberration for telescopes used for position measurements and must be carefully corrected for. A simple example of this is when the field is stretched across the focal plane in Schmidt telescopes. It is often caused by incorrect alignment of secondary optics but can affect mirrors produced with high order polynomial shapes.

4.1.3 Focal Points

The preceding discussion explained the dangers associated with the image not truly representing the observed object due to imperfect optics. As was mentioned, there are methods for correcting these problems, which involve using secondary, ternary or later mirrors to change the light path and correct the problem. Because of this, it is possible to place instruments in different locations, depending on which aberrations are acceptable and which are not.

The most basic focal point is the prime focus of the system, which is where the reflected light first reaches. In this location it is possible to correct some aberrations using a refracting plate placed in front of the detector. Prime focus allows for the widest field of view and so is used for wide field cameras. The secondary mirror is also placed near prime focus, if a different focal point is to be used. The Cassegrain focus is another commonly used focal point. It requires only a secondary mirror and causes the image to form behind the primary mirror, necessitating a hole in the primary mirror for the light to pass through. The Nasmyth and Coude systems use two and three mirrors respectively, to cause the image to form to the side of the telescope. The Cassegrain and Nasmyth foci provide smaller fields of view while the Coude system provides the smallest field of view and is often used in optical interferometry systems.[5]

Thus, all modern telescopes have instruments at different focal positions and the instrument selected depends on the observation being performed. For example, the Subaru telescope (Figure 6) has the Suprime camera at the primary focus, the OH Airglow Suppression Spectrograph on the right Nasmyth

[5] Described in section 4.3.

mount, the High Dispersion Spectrograph on the left Nasmyth mount and an adaptive optics system[6] coupled to four other instruments at the Cassegrain focus. The observer simply selects the instrument they wish to gather data with and the light is focused to that instrument, removing the need for instruments to be manually moved in and out of place, which is a significant cause of misalignments.

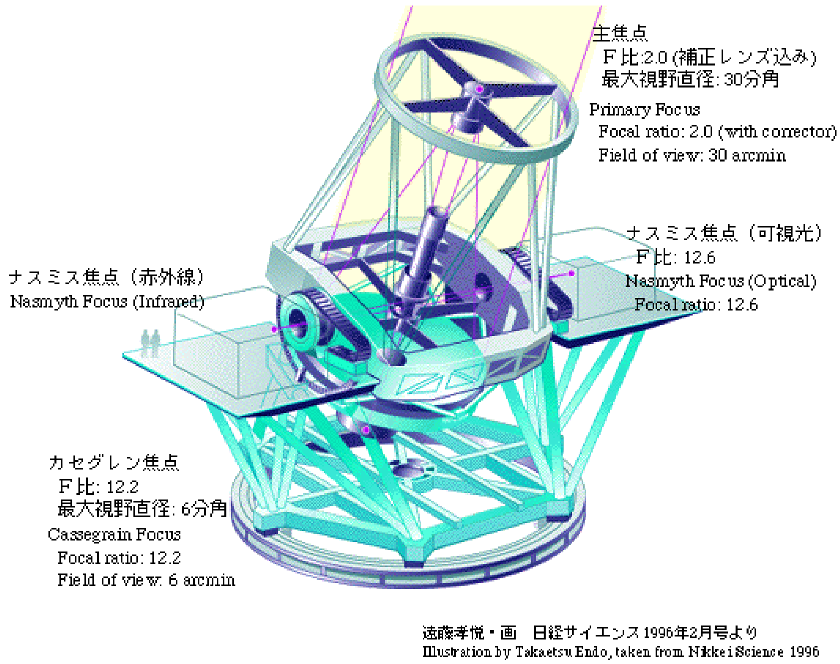

Figure 6: The Subaru telescope focal points. The Cassegrain focus contains four instruments plus the adaptive optics system, while the other the foci contain a single instrument each [5].

4.2 Active/adaptive optics

In the quest for the best possible optical configuration, it has become apparent that simply building larger and larger mirrors is not practical, nor feasible. Very large mirrors will deform under their own weight, while mirrors of any size are affected by atmospheric distortion. It is also difficult to mill a mirror to a precision of better than the wavelength even for mirrors with more reasonable sizes. Thus many new telescopes have active corrective systems to correct the shape of the mirror.

Whenever a plane wave passes through an aperture of diameter D the wave crests spread out. If light of wavelength λ from two sources separated by an angle θ passes through this aperture, destructive interference will occur where the wave crests differ by $\lambda/2$, while constructive interference will occur where the crests are together. Since we can assume $\lambda \ll D$, the small angle approximation gives the distance between interference minima as λ/D. A more detailed analysis results in the diffraction limit

[6] Described in section 4.2.

formula,

$$\theta = 1.22 \cdot \lambda / D. \tag{4.4.2.6}$$

Thus, even a very large telescope will have a minimum angle that it can image. A larger aperture—primary mirror diameter—will thus be able to image a smaller angle. But because of atmospheric effects, this limit is never reached for large ground-based optical telescopes. Adaptive optics is used to adjust the incoming light path to allow a large telescope to more closely approach its diffraction limit.

By producing the largest possible mirror with the fewest defects, it is possible to achieve very high resolution and excellent light gathering power. However, larger mirrors will deform under their own weight and a eight meter diameter glass mirror has a lot of mass. Thus, in order to produce larger mirrors it becomes necessary to make them thicker to prevent this distortion. A thicker mirror increases the mirror's weight and makes it more difficult to mill. This problem is what prevented construction of mirrors larger than six meters for many years. With newer ceramic materials it has become possible to produce mirrors of necessary lightness, but the problem of deformation still exists. The current strategy is to actively correct for mirror deformation using a process called "active optics."

The 8.2m Subaru telescope on Mauna Kea is a prime example of this technique [5]. The primary mirror has a thickness of 20cm and weights 22.8 metric tons and is the largest single piece mirror in the world. This mirror was milled with a mean surface error of only 14nm. Because of the how thin the mirror is, it is necessary to adjust it several times per second with over 260 actuators which correct for any deformations which do occur. The Subaru telescope has been able to reach an angular resolution about 0.3arcsec in the visible wavelengths due to a combination of their site, excellent mirror quality and a unique dome design to reduce internal temperature variation and turbulence. However, considering that at 500nm the diffraction limit (eq 4.4.2.6) of Subaru is about 0.015arcsec, it is not being used to its maximum potential.

Very rapidly-adjusting mirrors and advanced processing techniques open up the possibility of actively correcting for atmospheric conditions. The basic techniques of adaptive optics were developed in the 1980s by the U.S. military and were released to the astronomical community in the early 1990s. Essentially, a secondary, ternary or later mirror is mounted on a set of servos which allow the mirror's shape to be modified on time scales of order a millisecond and to near-nanometer precision. A computer examines the image of a bright star in the field of view and adjusts the mirror so that the star is as close to a point source as possible. For some telescopes which do not have enough light gathering power to use any star for this purpose, a laser guide star is use. In this case, a laser beam is reflected off a layer of the upper atmosphere and the reflected light is compared with its original shape and structure. A computer then corrects the secondary mirror to make the laser's light match its original appearance. Subaru, using ordinary guide stars, is able to approach its diffraction limit with an adaptive optics system placed at the Cassegrain focus.[7] They have achieved better than 0.06 arcsec resolution for observations in the visible [5], which rivals the HST. The Subaru system is not yet fully optimized, so its resolution should increase in the next few years.

4.3 Interferometry

To achieve very high angular resolution, it is necessary to produce a larger primary mirror surface, as shown above. But there are practical limits to the maximum size of a mirror, due to weight, cost and mobility. Thus, as the diffraction limit (eq 4.4.2.6) depends on the diameter of the primary but not its area, it is possible to combine multiple telescopes to produce a telescope with effective diameter equal to their separation. This technique, known as Interferometry, has been used at the Very Large Array (VLA) in radio wavelengths for over twenty years and is now being applied to optical wavelengths. The Very Large Telescope Interferometer (VLTI) at Cerro Paranal, Chile is using this technique with four 8.2m telescopes with maximum separation of 200m [8]. For optical interferometry, it is necessary to constructively combine observations from multiple telescopes, which requires better than one wavelength precision in the optical paths. More information on this subject can be found in [3, pg 149].

5 Long wavelengths

Space does not permit a detailed discussion of the techniques used for long wavelength astrophysics. What follows is a brief summary of some of the methods used in radio and infrared astronomy.

[7] For detail on focal points, see section 4.1.3.

5.1 Radio: 1mm - km

Similar to the visible region, the radio region has been throughly studied but many questions still remain. The basic telescope design is essentially the same as for visual telescopes, though the reflecting surface need not be milled to such a high precision.[8] Spherical mirror designs are also often used, as the antenna can be designed to receive a signal focused to a line, thus avoiding the problem of spherical aberration. Due to the wavelength dependence of the diffraction limit (eq 4.4.2.6), it is difficult to make a single radio telescope with sub-arcsecond resolution. Currently, the radio telescope with the highest resolution is also the largest telescope in the world: the Very Long Baseline Interferometer (VLBI) has an effective diameter of about 8600 km. By combining telescopes scattered across the United States, the Carribean and Europe using radio interferometry, it has achieved resolutions better than 10^{-4}arcsec in the millimeter realm [3, pg 145]. Radio interferometry is easier than optical interferometry as the phase information can be readily recorded and combined later, so long as the signal timing is recorded very precisely.

5.2 Infrared: 900 nm - 1 mm

Observational techniques used in the infrared are very similar to those used in the optical. Many optical telescopes do perform IR observations, though ground-based telescopes suffer from the problems of atmospheric absorption and emission. Another significant problem with IR telescopes is that the telescope and detector themselves produce heat which adds noise to the observation. Thus, advanced cooling techniques are necessary to keep the noise low. Many detectors are cooled to around 100K, significantly reducing the instrument noise. Space based telescopes benefit greatly here, due to the lower ambient temperature. Thus, the Infrared Space Observatory (ISO), the Cosmic Background Explorer (COBE) and the Hubble Space Telescope (HST) all make use of passive cooling to keep their IR mirror and instrument temperatures below 100K. Both ISO and COBE used liquid helium to reduce their temperatures to below 20K. In this manner, COBE was able to perform a detailed map of the cosmic microwave background (CMB) determining that it resembled a blackbody of temperature 2.72K between .5mm and 5mm, with a maximum deviation from the theoretical spectrum of only 0.03% [3, pg 105].

[8] Radio telescopes are often seen with mesh as the reflecting surface, since the mesh spacing is often much smaller than the observed wavelength.

6 High energy astrophysics

At very high energies, the distinction between the telescope and the detector begins to be blurred, as it becomes harder and harder to focus the incident light. In this realm, the particle nature of light is the most important and detectors cannot ignore quantum effects which would otherwise be unimportant at lower energies. It is also the region where some of the strangest sources are found, having temperatures in the millions of degrees and magnetic fields of hundreds of Tesla. There are many sources of such radiation beyond just high temperature blackbodies, including antimatter annihilation, inverse Compton scattering, synchrotron radiation, high energy particle collisions, and relativistic interactions with the cosmic microwave background.

6.1 X-rays: 10^5eV - 10^2eV ($<$ 10 nm)

Cosmic X-ray sources were first discovered in 1962, by a group led by Riccardo Giacconi [2, pg 2] and this region has since yielded very important information. However, standard mirrors do not work for observing X-ray sources. As any metallic surface will simply absorb the photons, new techniques had to be developed. The standard method is that of grazing incidence telescopes, as shown in (Figure 7). By using multiple nested mirrors the effective area of the detector is increased. This area is not constant at all energies, so for instance the Advanced CCD Imaging Spectrometer aboard the Chandra X-ray observatory has an effective area of over 700cm^2 just above 1.0keV, but under 100cm^2 for all energies below 0.3keV [9]. The telescope geometry and mirrors must be tailored to a specific energy and each telescope has its own optimal range.

Because of our atmosphere, astronomically-produced X-rays are invisible to observers on the ground. Thus all observations of X-ray sources occur either with very high altitude balloons or with orbiting observatories. There are currently several such space telescopes in orbit, run by NASA, NAOJ and ESO. These observatories cover much of the X-ray spectrum, from 0.1keV for Chandra's High Resolution Camera to 60keV for the Rossi X-ray Timing Explorer's Proportional Counting Array [9].

6.1.1 Telescope design

As mentioned above, normal incidence reflecting telescopes are not appropriate for X-ray imaging, while refracting surfaces are essentially useless in focusing X-rays. An incident X-ray normal to a surface will

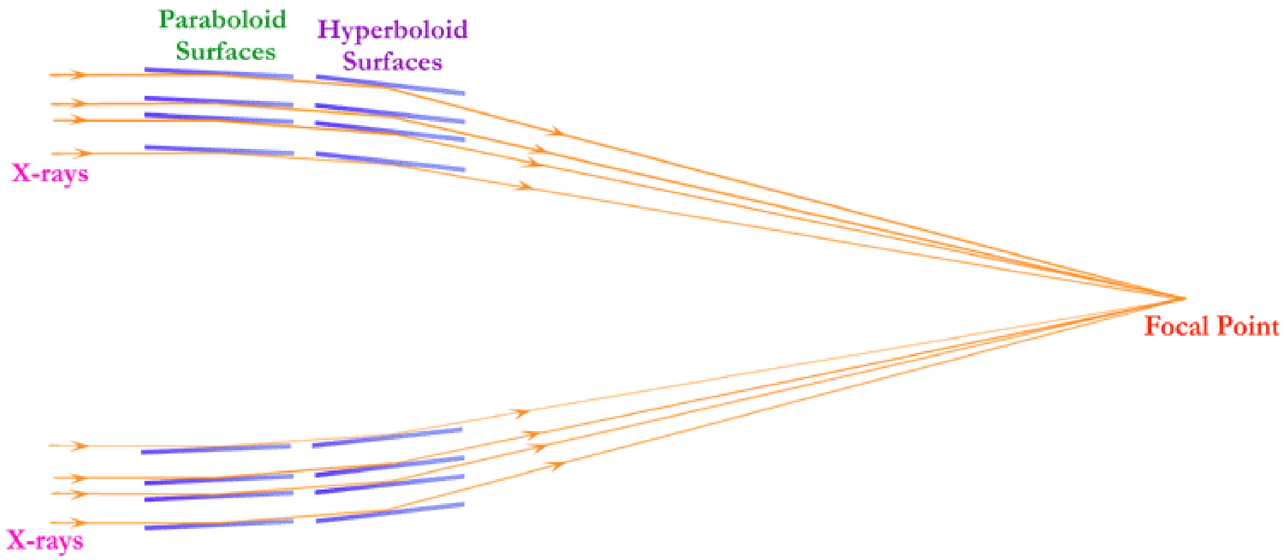

Figure 7: Basic design of a Wolter I grazing incidence telescope. This basic shape is the same as what is used in more advanced polynomial designs [10].

generally pass through unhindered, or simply be absorbed by the material. Grazing incidence makes use of total external reflection—similar to total internal reflection as seen in crystals and fiber-optic cable. The current design utilizes a double mirror system (Figure 7) with paraboloidal and hyperboloidal mirrors. This basic system has no spherical aberration but suffers strongly from coma, field curvature and astigmatism. Hans Wolter did the primary design work in 1952 [10] when he proved that any system with an odd number of conic sections would not satisfy Abbe's condition[9], while an even number could. Newer mirror designs will use high order polynomials based on modification of the coefficients of the spherical mirror (eq 4.4.1.5) to increase the off-axis resolution while slightly reducing on-axis performance [11].

For X-rays, the index of refraction, n, is always close to unity, since they are essentially not deflected by any surface and any deviation is caused by scattering off of electrons. Thus, the index will depend on the number density of electrons in the material, so the theoretical formula for X-rays incident on a surface is given by [12, pg 2]

$$n = 1 - \delta = 1 - \frac{1}{2\pi} r_e N \lambda^2, \tag{6.6.1.1}$$

[9]Abbe's condition states that an optical system will form an image if the principle surface (the intersection of the initial and final light paths) is spherical. This condition is easy to satisfy for paraboloidal optical telescopes by using a correcting lens or secondary optics [10], but is more difficult for off-axis designs such as are used in X-ray telescopes.

where r_e is the classical electron radius, N is the number of electrons per cubic meter of material, and λ is the incident wavelength in meters. Thus, since the atomic number, atomic mass and material density determine the electron density in a substance, we have

$$\delta = (2.72 * 10^{17}\text{m})\frac{Z}{A}\rho\lambda^2, \tag{6.6.1.2}$$

where Z is the number of electrons in the group (typically atomic number, though possible representing a molecule or crystal lattice), A the atomic mass number, and ρ the density of the material. The critical angle of incidence can be found in the same manner as for standard refracting systems,

$$Cos(\theta_\text{c}) = n \qquad \Rightarrow$$

$$\theta_\text{c} = Cos^{-1}(1 - (2.72 * 10^{17}\text{m})\tfrac{Z}{A}\rho\lambda^2). \tag{6.6.1.3}$$

For standard materials and a wavelength of 1nm, this value is less than one degree, but for 1nm light incident on gold (Z=79, A=196.97, ρ=19.3g/cm^3), we have $\theta_\text{c} = 3.72°$. Thus the mirrors on modern grazing incidence telescopes are coated with a thin layer of gold or iridium (which is also very dense) to allow for the maximum possible incidence angle.

6.2 Gamma-rays: $>10^5$eV

For photons of energies beyond about 50 keV, even more drastic techniques are required for their measurement than those used for softer X-rays. It is currently not possible to focus gamma-rays using the geometrical methods described above, though there are some very recent design plans for such systems [13]. Gamma-ray observations from space were carried out by the Compton Gamma-ray Observatory (GRO) until its deorbiting in June 2000. Ground-based observations are performed through a variety of methods, all of which involve searching for the products of gamma-ray impacts with the atmosphere.

For ground-based observations, the use of Cerenkov detectors has been the norm for many years. If a particle passes through a medium with a speed faster than the speed of light in that medium, Cerenkov radiation results. As they pass through our atmosphere, high energy photons produce relativistic positron-electron pairs with enough velocity to produce Cerenkov radiation. Ground-based

Cerenkov detectors consist of mirrors, similar to optical telescopes but with their light focusing on one or several photomultiplier tubes. From the mirror configuration and timing information, the direction and incident energy of gamma-ray strikes on the atmosphere can be determined. One of the largest problems is determining which events are gamma-ray strikes and which are high energy hadrons. Extensive Monte Carlo simulations [14, pg 110] have been used to model gamma-ray and hadron strikes to attempt to reduce the noise, but errors are still about 10% for even the best instruments.

6.3 Cosmic rays

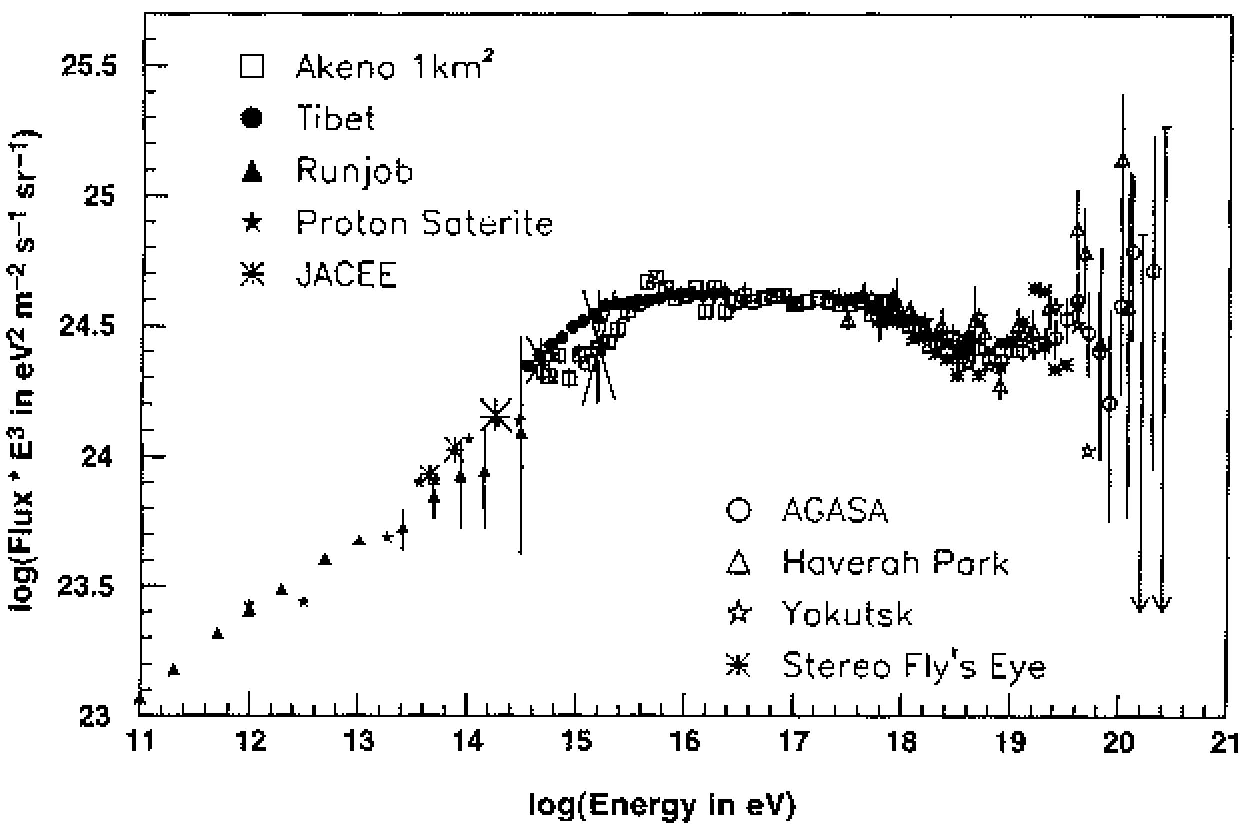

Figure 8: The cosmic ray spectrum from 10^{11}eV -10^{21}eV. Visible are the knee at about 4×10^{15}eV, ankle at 5×10^{18}eV and a small number of detections above 10^{20}eV [15, pg 74].

In the realm of extremely high energy particles, observational astronomy begins to probe the limits of our understanding of particle physics. Particles have been detected with energies above 10^{20}eV, which is more than 50 J in a single particle! It is currently impossible to create particles in earth-based laboratories with energies greater than 10^{12}eV and so these studies shed light on otherwise unavailable regions of the spectrum. Generally similar in design to the atmospheric Cerenkov detectors described above, cosmic ray detectors such as the High-Resolution Fly's Eye detector use multiple mirror/PMT combinations to map the direction and energy of incoming cosmic rays. The displayed spectrum (Figure 8) shows the observed cosmic ray flux on the earth above 10^{11}eV. The structure of this spectrum is not yet understood, nor are all the methods producing particles of these high energies.

7 Conclusions

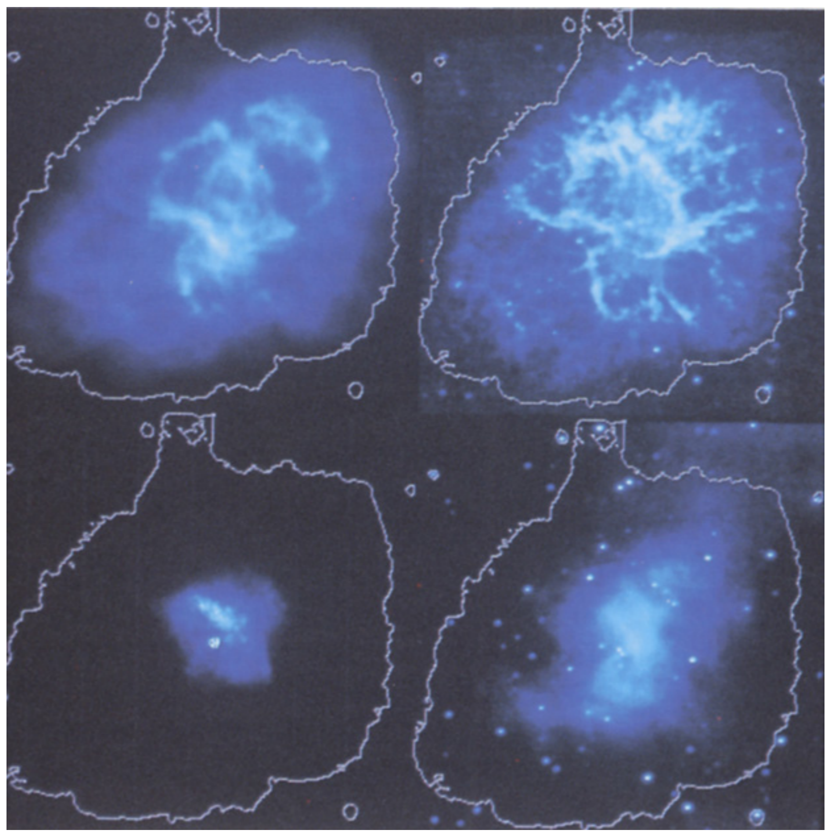

Figure 9: The crab nebula in four wavelengths, with equal scale and orientation. Clockwise from the upper left: 20cm VLA radio, Hα at 656.3nm, blue/UV electron synchrotron radiation, soft X-ray. The pulsar is visible in the X-ray image as the bright point near the center [2, pg 81].

As an example of the necessity of observing across the spectrum, (Figure 9) shows the crab nebula in four very different wavelengths, each of which describes a different aspect of the source. The radio image maps the diffuse, low temperature gas while in Hα emission the hotter hydrogen regions are visible. The UV image displays the regions in which electron synchrotron radiation is occurring, thus mapping the internal magnetic fields of the structure. In soft X-rays the nebula looks very different and the pulsar is readily visible as a slightly off center point source. The small amount of light coming from the region near the pulsar itself is a region of very strong magnetic field and very high temperature where synchrotron X-rays are generated. The contour on each image gives the maximum extent of the nebula, as mapped by doubly ionized oxygen. The Very Large Array (VLA) acquired the radio image and provided a very high resolution due to its use of interferometry. The near-UV image required a high altitude observatory to avoid atmospheric attenuation. The resolution of the X-ray system required a focusing system, which was provided by the Einstein telescope using a design similar to the one described above (Figure 7). Since these images were released, there have been much more detailed studies of the Crab nebula, including a very detailed map by the Chandra X-ray observatory. Each of these wavelengths describes something new about this source and without observations in each of these bands, our knowledge of this pulsar and nebula would not be complete.

In closing, I would like to quote from Bruno Rossi, one of the pioneers of X-ray astronomy and a leader in the design of new telescope systems [16, pg 1161].

> To watch the growth of this new branch of science (X-ray astronomy) has been one of the most exhilarating experiences of my whole life as a scientist. The unexpected and astonishing results that have been following one another in quick succession have been for me a striking illustration of how much the imagination of man lags behind the boundless wealth and complexity of nature.

This statement holds true for more than just his realm of high energy astronomy. A claim is often heard that there is no new work to be done in well studied spectral regions such as visual or radio. This consistently proves to be false however. For example, nearly every month the HST releases an image containing an object or interaction which was previously unimagined. Though nearly all of the spectrum is currently covered,[10] not all regions are covered equally well and the highest and lowest energies are still not being imaged. Undoubtedly there are as yet undiscovered objects awaiting detection and new information to learn about already known sources.

[10] Medium energy gamma-rays are the only spectral region currently not being imaged, due to the Compton Gamma-ray Observatory being deorbited.[17] The Gamma-ray Large Area Space Telescope is a NASA mission planned for 2005 to make observations in exactly this region.[18]

A The photoelectric effect

Most modern astronomical detectors use some form of the photoelectric effect. Described in Einstein's paper of 1905, the general result is due to the quantization of energy. A conducting surface represents a potential barrier of energy ϕ (the work function). If an incoming beam of photons has at least this minimum energy, the surface will release photoelectrons with kinetic energy equal to the difference between the photon energy and the work function

$$E_k = hf - \phi, \tag{A.A.0.1}$$

where hf is the energy of the photon [1, pg 1150]. A photomultiplier tube (PMT) makes direct use of this effect. The incident photon releases an electron from a conducting surface which is then accelerated across a potential difference to another conducting plate. This electron strikes the plate, releasing more electrons and the process continues over several more plates. The resulting charge cascade strikes an anode producing a strong current. Since the first electron will have an energy as given above (eq A.A.0.1) and each subsequent release will depend only on the energy of the previous group of electrons, the observed charge will be proportional to the energy of the incident photon.

It is also possible for a incident photon with energy below ϕ to ionize an atom on the surface of a material. A semiconductor crystal, such as silicon, will release electrons into its crystal lattice which can be drawn away to a potential well via a potential difference. Once a significant number of charges have been drawn off in this manner, their total charge can be read out, providing information about the number of photons that had struck the surface. By doping the semiconductor with different substances, the energy range and sensitivity of the material can be modified to fit the necessary region [3, pg 300].

Photons with very high energy can perform the same function in a gas, as opposed to a solid surface. A very high energy photon ($hf \gtrsim 10$eV) will ionize atoms in the gas. The released electrons can be accelerated by a potential difference and cause more ionizations through collisions. When the resulting charges reach the electrode, they produce a current linearly proportional to the incident photon's energy. At some maximum energy, the incident photon will either short out the chamber or have too small of an interaction cross section for photoionization to be useful [3, pg 305].

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