The Search For Planets Around Other Stars:

Dancing In The Dark

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"There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous. The countless worlds in the universe are no worse and no less inhabited than our Earth."

- GIORDANO BRUNO (1584)

Introduction

In scribing these words, the medieval Catholic monk Giordano Bruno succinctly expressed the 21^{st} century beliefs of many scientists who now search, successfully, for planets around other stars. Even more remarkably, Bruno neatly summarized the observational challenges as well! Unfortunately for the reputedly contentious Bruno, he was born 400 years too soon, and instead of accolades for his foresight and strong opinions, he was tried for the crime of heresy, and burnt at the stake in 1600. Although beliefs similar to Bruno's have often been expressed in the centuries since his death (with far less catastrophic consequences, thankfully!), it has only been in the last century that we have developed the techniques to provide the scientific underpinnings to this philosophy. And in the last decade, we have seen the search for other worlds evolve beyond the realm of heresy and science fiction, into science theory, and finally, into science fact.

We live in very exciting times! As this chapter is being written, we now know of over 100 planets outside our own solar system. All of these planets have been discovered using existing telescopes, but over the next two decades we will build and fly special space-bourne observatories to expand our knowledge of the number and distribution of planets in our Galaxy, and whether or not these planets might support life. This chapter will describe the observational challenges and techniques used to discover extrasolar planets, and will provide an overview of future missions to detect extrasolar planets. The companion chapter "The Search For Habitable Worlds" will explore the currently theoretical field of extrasolar terrestrial planet characterization. It will describe how we might one day use astronomical techniques to understand the new worlds that we find, and how we will determine whether they or not they are habitable, and how we will look for signs of non-technologically-advanced life. But first, let's discuss the incredible challenge of even *detecting* an extrasolar planet!

The Observing Challenges

Sesarching for planets around other stars is no easy task. As Bruno pointed out, at visible wavelengths (0.3-1.0μm), planets don't produce any light of their own. We would see them via the reflected light from their parent star. However, luckily for us they are not, as in Bruno's assessment, "invisible", but rather *extremely* faint! At visible wavelengths a planet the size of the Earth, at the same distance from its parent star as the Earth is from the Sun, is typically a billion (10^9) times fainter than its parent star, or about 30^{th} magnitude.

Figure 1: This diagram shows the brightness difference (contrast) between a star and its planet as a function of wavelength. At mid-infrared wavelengths, the contrast is a million to one. At visible wavelengths, the contrast ratio is closer to a billion to one. Major constituents of planetary atmospheres are labeled at their respective wavelengths and the purple band denotes a wavelength region that has a low-contrast ratio, and is particularly rich in atmospheric bands.

This is so faint, that using standard observing techniques, the planet would be lost in the glare of the parent star. Put another way, trying to observe a planet at visible wavelengths around the closest star to our Sun, Proxima Centauri, is like standing in Sydney and trying to see a moth around a search light in Perth! Moving into the infrared region of the spectrum improves the contrast ratio to a mere million to one, but this is still unachievable with present technology. In addition, planets (at least the ones that might be habitable, and therefore that we are most interested in) tend to be close to their parent star. When viewing them on the sky, telescopes with very large collecting areas are needed to provide enough "angular resolution", that is, the ability to separate ("resolve") the planet from its parent star (or the moth from its searchlight!) Because of the dual problems of the planet/star contrast ratio, and insufficient resolution, direct detection of planets around other stars is beyond present technology. How then, have we discovered so many planets around other stars?

Indirect Detection Techniques

The first thing we have to understand is that all of the planets found outside our solar system have, in fact, *never been seen!* Instead, these planets are known to exist via "indirect detection techniques". That is, the presence of the planet is inferred from observations of a star, whose brightness or position is altered by the planet. Below, we will review four of the most widely-used indirect detection techniques for extrasolar planets.

The Doppler Method

Also know as the *radial velocity technique*, this method has resulted in the most planet detections to date. It was pioneered by the Swiss astronomers Queloz and Mayor, and the U.S. astronomers Marcy and Butler. This technique takes advantage of the fact that when a planet orbits a star, the planet and the star are in fact orbiting a common center of mass. As the planet orbits the star, the star will appear to "wobble" or "dance" in the sky as the two bodies move around their common center of mass. The larger the planet, or the closer the planet to the parent star, the larger the wobble. This technique therefore favors the detection of large planets, close to the parent star.

Figure 2: Planets discovered using the Doppler technique. This plot shows the first few AU of our own solar system architecture at the top, and compares our solar system with the mass (expressed as Jupiter masses, M_J) and distance from the parent star of extrasolar planets found using the Doppler technique. Note that the majority of planets found using this technique are large, and many are closer to their parent star than we see in our solar system. This does not necessarily mean that these types of solar system architectures are the norm and that our own solar system is unusual!

Instead, this plot shows in large part that the Doppler technique is most sensitive to discovering these types of architectures.

To detect the dance, the astronomers use another piece of physics, that of "radial velocity shifts". When a star moves towards us, the light from the star is said to be "blueshifted" via the Doppler effect. That is, light of a particular wavelength emitted in the rest frame of the star, will arrive at our detectors on Earth at a wavelength that is bluer than its rest frame wavelength. Similarly, if the star is moving away from us, its light will appear to be redder than it would be in its rest frame. As a planet and a star orbit around their common center of mass, the star will appear to move towards and away from us, alternately blueshifting and redshifting its light. The faster the planet moves towards or away from us, the larger the wavelength shift.

However, even for a relatively fast moving planet close to its parent star, these wavelength shifts are very, *very* tiny, and depending on the orbit of the planet, may take several years to appear as a repeating pattern in spectral measurements of the star. Nonetheless, using spectral observations of stellar metal lines (whose rest-frame wavelength is known very accurately), and by observing through an iodine gas reference source, astronomers were able to observe very accurate wavelength shifts, and detect the "in and out" wobble on the sky of stars with planets.

By observing this behaviour over days or years, the astronomers were able to fit the wobbles with mathematical functions from which they could derive the period, distance from the parent star, and set limits on the planet's mass. They can also use this technique to discover stars with multiple planet systems and disentangle the contribution to the observed stellar velocity curve due to planets of different distances and masses (Figure 3).

Figure 3: Detecting multiple extrasolar planets using the Doppler technique. These plots show mathematical fits to radial velocity differences for stellar metal lines as a function of time. The changes in observed radial velocity for the star (Upsilon Andromedae) are due to the presence of three planets! The top panel shows a poor fit from attempting to fit the data with a single planet. The middle panel shows the much crisper fit once the effect of multiple planets is taken into account, and the bottom panel shows a schematic representation of the planetary orbits in the Upsilon Andromedae system.

However, the masses of planets derived using the Doppler technique is only a lower limit (the smallest mass the planet could have) because of an ambiguity introduced by not knowing how the planet's orbit is projected along our line of sight. When the pole of the planet's orbit is pointing perpendicular to our line of sight, we will see the full effect on the star of the planet's mass, and can derive the correct mass. However, for all other possible orientations between perpendicular and along our line of sight (when we wouldn't be able to detect any radial velocity shift!) the perturbation observed will be a function of $M/\sin(i)$, where i is the inclination of the orbital pole to our line of sight. The Doppler technique, not being able to independently determine i, can therefore only provide a lower limit on the mass of the planets it finds.

The Doppler technique has been a fantastic success and the forerunner in extrasolar planet detection. The future of this technique will concentrate in two areas: continuing to observe the target stars to detect planets with longer orbital periods (at least two full periods must be observed to claim a detection), and working to dramatically reduce the systematic measurement error.

However, there are some limitations to this technique. To detect very small radial velocity shifts, a large amount of light needs to be collected, and with the current telescope collecting areas available, these searches are limited to nearby, bright stars within about 100 light years. Even with larger telescopes, which would open up the ability to search more of the nearby solar neighbourhood, this technique cannot easily detect planets very much smaller than Neptune. This is not a limit in the technology, but rather a fundamental physical limit. For planets smaller than Neptune, the velocity shifts due to the planet are masked by noise in the velocity shifts from the atmosphere of the star itself (typically $3ms^{-1}$). This velocity shift corresponds to a minimum detectable mass of $33M_e$ $/\sin(i)$ for a planet at 1 AU from a one solar-mass star, where i is the inclination of the orbital pole to the line-of-sight and M_e is the mass of the Earth. However, if we are able to better understand the nature of convection on the stellar surface, and we can measure the profile of the stellar lines to very high precision, we may be able to remove the effect of the stellar atmosphere and push down below the $3ms^{-1}$ limit. If this strategy were successful, it would drive the lowest planetary mass detectable by this technique down to as little at 10 Earth masses, but probably no further. The Doppler technique has therefore been our best pioneer technique is the search for extrasolar planets, but it cannot be used to find the ultimate prize, the smaller Earth-sized planets in life-supporting orbits.

Astrometry

This technique uses physical principles very similar to the Doppler technique. That is, the planet is inferred from the "dance" of the star as it orbits the common center of mass. However, whereas the Doppler technique looks for the "in and out" component of the motion of the star perpendicular to the plane of the sky, the astrometry technique looks for the "side to side" component of the dance projected in the plane of the sky. This apparent change in position of the star on the sky, relative to a frame of distant positional standard stars, is very tiny! However, this technique, is, in some ways complementary to the Doppler technique because it is more sensitive to smaller mass planets further from their parent star.

To make measurements using this technique, the Keck telescope in Hawaii is being equipped to measure angles as small as 20 μ-arcseconds. This translates to a minimum detectable mass of 66 Earth masses for a planet at 1AU distance from a solar-mass parent star 10 parsecs away. For space-based instrumentation, the Space Interferometer Mission will attempt to detect planets as small as about 7 Earth masses at 1AU from their parent stars, which can be up to 10pc away. To do this, it will need a positional accuracy of 2 μ-arcseconds, 10 times better than will be achieved from the ground.

Figure 4: Using the Astrometry Technique to Detect a Planetary System: Our own Sun would reveal the presence of its planetary system to an observer at 10 parsecs away by systematically changing position on the sky in response to the gravitational pull of the large planets as seen above. The dominant sources of the motion are due to Jupiter and Saturn.

One advantage that this technique has is that the two-dimensional astrometric information obtained uniquely defines the orbital inclination of the planet, and hence a unique mass (since the distance is known accurately via parallax). However, this method is currently limited by the apparent brightness of the parent star, and would work best for main-sequence stars within 10pc of the Earth. There are only 33 non-binary solar-like stars within this limit. From the ground, the technique is also limited by our ability to accurately measure the star's position through a shifting, variable atmosphere. And as is also the case for the Doppler technique, the furthest planet from its star that can be detected is limited to the time needed to observe at least one orbital period. For reference, Jupiter, at 5AU from the Sun, has a 12 year period! As this chapter is being written, there are no planet detections yet confirmed using the astrometry method.

Transit

Unlike the Doppler and Astrometry techniques, the transit technique does not look for changes in the parent star's *motion* due to the presence of the planet, but rather, for changes in the *brightness* of the parent star. In our own solar system, when a planet passes between us and the Sun, the light of the Sun is dimmed as the planet blocks a tiny fraction of the Sun's disk. Similarly, when an extrasolar planet moves across the face of its parent star as seen from our vantage point, the light of the parent star is dimmed (Figure 5). As the planet orbits its star, the light will dim periodically. The amount (amplitude) of the dimming, and the time that the light of the star stays suppressed can be used to derive the planet's size, and distance from the star.

Figure 5: The transit technique. This simple diagram illustrates how the transit technique detects an extrasolar planet. As the planet moves across the face of its parent star along our line of site, the overall brightness of the star is progressively dimmed. Astronomers can use the amplitude of the dimming (the brightness difference between 1 and 3) and the period of the dimming (the time interval over which the light is dimmed) to determine the planet's size and distance from the star.

To claim a planet detection, astronomers will look for consistent repeatability of the period of the dimming (that is, the time interval between dimmings), and the brightness change and its duration, over at least three cycles. This technique yields more accurate information regarding the size of the planet and its orbital characteristics than is possible using any other current method. Transit searches also enable astronomers to monitor more stars in a shorter period of time and extend the stellar search space to 100 million or more.

The first discovery of an extrasolar planet via the transit technique was announced in early January, 2003, and is awaiting confirmation. A team of US researchers discovered a Jupiter mass planet orbiting around a 4 billion year old star in Sagittarius, a staggering 5 000 light years away. This is more than 20 times farther away than any currently known planet orbiting a normal star, and the parent star is in a different arm of the Milky Way to our Sun! The planet, designated OGLE-TR-56b orbits its star every 29 hours at a distance 50 times closer to the star than the Earth is to the Sun.

Interestingly, the planet's discovery and characterization was via a combination of techniques. The planet was discovered during the execution of the Optical Gravitational Lensing Experiment, which monitors the brightness of thousands of stars looking for brightening produced when an object passes between us and the star (see the section on gravitational microlensing below). Instead of a brightening though, they saw a periodic dimming for objects transiting 59 candidate stars. To determine whether these objects were planets, or more likely, faint stellar companions, the team took spectra of the candidate stars using a relatively small telescope. They used the large radial velocity shifts seen via the Doppler technique to eliminate all but 5 candidates as having stellar companions, rather than planets. For the remaining candidates which showed little or no radial velocity shift, indicating an extremely low-mass companion, the team used the Keck telescope in Hawaii, the largest optical telescope in the world, to measure the tiny radial velocity shift that indicated that OGLE-TR-56 had a 0.9 Jupiter mass companion. From the magnitude of the dimming during the transit of the star, the team had derived a planetary diameter about 1.3 times that of Jupiter. Having the mass from the radial velocity measurements, and the diameter from the transit measurements, the team could prove that the planet was a gas giant, similar in density to Saturn.

Interestingly, the transit technique, when used in conjunction with spectroscopy, can also be used to understand the composition of extrasolar planets. Scientists using the Hubble Space telescope to observe a transiting system that was known to have a giant planet crossing the face of its star. They took spectra in the yellow sodium lines and were able to see the absorption in these lines *increase* as the planet crossed the face of the star. This indicated that the atmosphere of the planet contained sodium, which was absorbing the light from the parent star as it passed through the planet atmosphere on our line of sight. This was the first detection of the atmosphere of an extrasolar planet.

Gravitational Micro-Lensing

Another technique to help us understand the number of extrasolar planets in our Galaxy is that of gravitational micro-lensing. This technique was first described by Einstein in 1936 when he showed that a star passing directly across the line of site from an observer to another star would gravitationally bend and focus the light of the star behind, and form a ring-like image. Other geometries produce different types of images, all of which are difficult to resolve from the star itself, and the net result is a transient brightening of the distant star. The chance of observing two stars so precisely aligned with the Earth is very small, so a very large number of stars must be monitored to ensure such an event is detected. As the lensing (intermediate) star passes along the line of site there is a smooth amplification of the light from the distant star. Typically microlensing events can be identified with some confidence because they have a well-defined curve, show the amplification effect independent of wavelength, and only occur once for a given star (the chance of a given star being microlensed twice is *very* low!). Behaviour that deviates from these characteristics most probably indicates stellar variability or some other phenomenon.

To use this technique to detect planets, we have to understand that if the lensing (intermediate) star can influence the light from a background star, so can the smaller gravitational field of a planet *orbiting the lensing star*. The orbiting planet will act like a "defect" of the smoother lensing effect of the star alone. In addition to the characteristic rise and fall in brightness of the background star due to the lensing star, there may be an additional anomaly on the curve if the background star passes behind the defect in the lens produced by the planet. In this case, the shape of the microlensing lightcurve will allow us to determine the mass ratio between the planet and its parent star. Like the transit technique, the planetary anomaly in the light curve will last only a few hours to a few days, and so observers must be constantly vigilant to observe the effect, often using global networks of observers to ensure constant time coverage.

Gravitational microlensing is most sensitive to planets orbiting a few to several AU from their parent stars, and the likelihood and duration of a lensing event increases with the mass of the planet. Jupiter-sized planets may produce anomalies that last for 1-3 days, whereas Earth-sized planets produce an effect that lasts for only a few hours. Microlensing events would need to be monitored with extremely high precision before Earth-mass planets could be detected using this technique, and this is currently not achievable. However, this technique is sensitive to Neptune-sized objects and larger a few AU from their parent stars. It therefore has the advantage of being able to discover solar systems architectures more like our own (a Jupiter mass object at 5AU). This can also be done relatively quickly, without acquiring observations over a complete orbit of the planet (12 years in the case of Jupiter) as is required for detection using other techniques. Also, planets around very distant stars can be detected even when the star is too faint to be seen, greatly increasing our potential sample, and being insensitive to parent star brightness

However, when using this technique, care must be taken to ensure that atmospheric distortions, stray moonlight, or stray starlight from neighboring stars are not confused with the light from the lensed star to mimic a planet detection. This is especially important, because any solar systems found will only be observed once, and will be sufficiently far away that follow-up observations will not be possible using current techniques. Gravitational microlensing therefore will not discover specific systems that can be followed up later, but instead is most valuable for providing statistics on the frequency of solar systems and improving our understanding of how common our own solar system is in the Galaxy.

Suitable Parent Stars

When we look for extrasolar planets the observing techniques can be divided into "field surveys" and "targeted observations". For the field surveys, large areas of the sky, and therefore large numbers of stars, are monitored simultaneously in the hope of capturing an event that may last for only a few hours. Field surveys are typically used for transit and gravitational microlensing searches. For the targeted surveys, specific lists of stars are selected for monitoring over several years. The Doppler technique typically uses targeted surveys. A number of factors must go into selecting these observing lists to maximize the possibility that the star may harbor a planet of interest. First of all, to be a suitable "parent" for planets, a star must live long enough for planets to form, and hopefully, for life to evolve. Massive, hot blue-white stars of the spectral classification O, B or A are typically 1.5 times the mass of our Sun ($M_{\odot}$) and age very rapidly, typically exhausting their ability to burn hydrogen in less than 2 billion years. Additionally, the Doppler technique requires stars cooler than mid-F for observational reasons. Stars hotter and more massive than mid-F are generally more active and have less spectral structure than cooler stars, thus making to more difficult to measure their Doppler shift.

It would seem, therefore, that the longer-lived, smaller, cooler stars would be the most desirable candidates around which to search for planets. And this is true, up to a point. However, there are other issues relating to the likely habitability of planets around cool stars that often push observers back towards more solar-type stars. If the star is very small and cool, as are the $0.5M_{\odot}$ spectral type "M" stars, then any planet in orbit around it that could hope to sustain liquid water on its surface would have to exist very close to the star. At these close distances, there is a good chance that the planet will become "tidally locked" to the star, and unable to rotate on its axis. With one hemisphere of the planet constantly baked, and the other in perpetual darkness, it is thought that life would be less likely, because eventually any atmosphere would freeze out on the "night" side. In addition, later type stars such as the M stars are subject to large amounts of flare activity and would therefore produce a very unstable radiation environment for an encircling planet. It is for the above reasons, that the majority of searches concentrate on studying stars of the spectral type F, G and K.

Another factor which may govern whether or not a star may harbor *Earth-sized* planets is a factor called "metallicity". The metallicity of a star is a measure of what fraction of the star is composed of elements heavier than helium. Current research indicates that the majority of the stars around which planets have been found have higher than average metallicity. However, since metallicity is measured at the surface of the star, there is some debate as to whether the star's metallicity is inherent, or acquired because it has planets. Some argue that the inherent high metallicity of the star favors planet formation, while others argue that once planets form, they may be lost into the parent star early in the history of the solar system, enhancing the metallicity of the star's outer atmosphere. However, this latter theory is currently not as popular as the intrinsic metallicity argument.

The Known Planets, or Why Bigger Isn't *Always* Better

The techniques described above have been used to discover 100 or so planets around stars predominantly in the spectral classes F, G and K. Interestingly, 12% of the stars surveyed have been shown to have planets. However, as stated earlier, these techniques are typically more sensitive to giant planets, and the "dance" detected by the Doppler and astrometry techniques is more pronounced if that giant planet is close to its parent star. Not surprisingly, all of the planets discovered using these techniques are "giant planets", typically as large or larger than our planet Jupiter. And surprisingly, many of the planets were found very close to their parent stars. Although this is what the survey techniques are sensitive to, a solar system architecture in which Jovian sized planets exist close to the parent star was *completely* unexpected and is still difficult to explain!

Part of the enormous attraction of searching for extrasolar planets is the possibility that these newfound worlds will be able to harbor life, or will already be inhabited. However, based on the example in our own solar system, the extrasolar giant planets are most likely to be gaseous with no solid surface, and are consequently considered an unlikely cradle for life. Although giant planets will probably have satellites that are more likely to harbor life, this may be very difficult to observationally confirm. This is because in addition to having to separate the light from the satellite's parent planet from its parent star, the satellite must also be able to be distinguished from its parent planet. Hence, if we are interested in finding and characterizing habitable worlds, we will first need to find Earth-sized planets.

The smallest planet found so far using the Doppler technique is about the size of Neptune, or 0.12 times the mass of Jupiter, and this planet at the limit of the technique's current sensitivity. Small, rocky, Earth-like terrestrial planets around "friendly" stars still elude us, and require either different techniques, or a space-based platform, or both.

The Search For Earth-Sized Worlds

Indirect Detection

As described above, current ground-based detection methods cannot detect earth-sized planets, either indirectly or directly. Consequently several new techniques for space-based direct detection of Earth-sized planets are being developed, and spacebourne missions are also being designed to use the indirect techniques of transit and astrometry from the more stable environment of space. The missions which use the indirect techniques will allow limited characterization of the individual planets that they find, but will principally concentrate on performing a census of Earth-sized planets in our extended stellar neighborhood. Those missions that strive for direct detection of Earth-sized planets could potentially allow characterization that is sufficiently detailed to determine whether the planet is habitable, or already supports life.

Spaceflight Missions For Indirect Detection of Earth-Sized Worlds

As discussed above, using the Doppler or astrometric techniques to detect Earth-sized worlds is currently considered impossible from the ground due to fundamental constraints in both techniques. Although the transit technique has been used from the ground to discover Jupiter-sized worlds, it is extremely difficult to use that technique from the ground to discover Earth-sized worlds. Transits by Earth-sized planets produce a fractional change in stellar brightness of 5-40 x 10^{-5} and last for only 2 to 16 hours. It is therefore extremely important to monitor the stars continuously to increase the chances of detection. Not observing a star for even a few hours might mean that you miss the transit! This photometric accuracy (to a few parts in 100 000) is also difficult to achieve from the ground due to atmospheric perturbations, which must be minimized. With these constraints, the photometer must be spacebased to obtain the precision required to detect the transit of an Earth-sized planet, and to avoid interruptions caused by day-night and seasonal cycles.

The Kepler and Eddington Missions

Two proposed space missions, NASA's Kepler mission and ESA's Eddington mission will use the transit technique to indirectly detect Earth-sized planets (and also Jupiter-sized planets close to their parent stars). The Kepler mission is scheduled for launch in 2007. This 1-meter diameter spacebourne telescope, with exquisite CCD photometric capability, is designed to continuously survey 100,000 main sequence stars. However, because it must monitor this very large number of stars to obtain a significant result, the vast majority of these stars will not be in our local solar neighbourhood, but rather in our "extended" solar neighbourhood, typically 200-600pc away (check). However, with this large sample, it will detect and characterize hundreds of terrestrial and larger planets in or near the habitable zone of their parent stars (The habitable zone is that region around a star in which an Earth-sized planet can maintain liquid water on its surface). The Kepler mission may find as many as 650 Earth-sized planets within the habitable zone. These missions will therefore provide a very large statistical sample to help us understand the distribution and how many Earth-sized planets there are in our Galaxy.

The Space Interferometery Mission

The Space Interferometry Mission (SIM) is a NASA mission scheduled for launch in 2009 . This mission will use optical interferometry, combining the light from two or more telescopes as if they were pieces of a single, gigantic telescope mirror. With this design, and the technique of narrow-angle astrometry, SIM will be able to determine the positions and distances of stars several hundred times more accurately than any previous program. This mission can therefore use space-based astrometry techniques to 1-2 μ-arcesconds to search for planets as small as 1 Earth mass around the few nearest stars, out to 5-10 Earth mass planets within 10pc distance. SIM will search 200 main-sequence stars for these large terrestrial planets. Where feasible, orbital solutions and planet masses will be derived. Once one planet is detected, the search will be extended for evidence of additional planets in that system. The Space Inteferometry Mission will also demonstrate the spaceborne interferometry and the pathlength control potentially needed for the more difficult direct-detection missions, such as the Terrestrial Planet Finder mission, which is discussed below.

Direct Detection

Direct detection of an Earth-sized planet is *extremely* difficult, as the glare of the parent star is between a million and a billion times brighter than the planet we are looking for! On top of the brightness contrast issue, we also need instrumentation that can attain a very high resolution to separate the planet from its parent star. However, direct detection gives us something that the indirect techniques do not, namely the ability to characterize the extrasolar planet's properties by obtaining measurements of the planet's brightness, color, spectral properties and time variability.

Techniques and Spaceflight Missions For Direct Detection of Earth-Sized Worlds

Direct detection of Earth-sized planets is currently believed to be infeasible from the ground. Consequently work in this area has concentrated on space-based means to detect Earth-sized worlds. These techniques use different means to achieve the same goal - to block the light from a parent star in order to see its much smaller, dimmer planets. Currently there are two candidate mission architectures under consideration, these are an infrared nulling interferometer, and a visible light coronograph

Infrared Nulling Interferometer

Using the technique of interferometry allows multiple small telescopes on a fixed structure, or on separated spacecraft flying in precision formation (Figure 6), to simulate a the angular resolution of a much larger, very powerful telescope. The interferometer would utilize a technique called "nulling" which relies on the principle of destructive interference to reduce the starlight by a factor of one million, thus enabling the detection of the very dim infrared emission from the planets (Figure 7). To build "pictures" the interferometer must rotate around its line of sight to different relative positions and repeat the "exposures." The interferometer could also obtain spectra of interesting targets.

Figure 6: Free-flying nulling-interferometer. This artists rendition illustrates a mission concept that would use free-flying spacecraft to collect and combine light to null out the light from a nearby star so that we can see its encircling planets.

Figure 7: Planet detection with a nulling interferometer. This diagram shows the nulling pattern with the star suppressed in the central null, and the planet visible in a nearby constructive interference band.

Visible Light Coronograph

For this proposed architecture, a large optical telescope, with a mirror three to four times bigger and at least 10 times more precise than the Hubble Space Telescope, would collect starlight and the very dim reflected light from the planets. With special optics the telescope would use the technique of coronography to reduce the starlight by a factor of one billion, and improve angular resolution, thus enabling astronomers to detect the planets.

In its simplest form, a coronagraph blocks the light from a bright object so that faint nearby objects and structures can be seen. Coronagraphs have been used to study the corona surrounding our Sun (hence the name!), and to search for faint, small companions of nearby stars. To study the area around a nearby star, the coronograph must not only minimize the direct light from the nearby bright object, but must also minimize the telescope diffraction, which will reduce the angular resolution of the image. A simple round telescope, for example, will produce a diffraction pattern that is dominated by a bright central spot, and a series of concentric rings of decreasing brightness. To see a planet, the first several bright rings must be suppressed without suppressing the planet. By using masks to simulate a telescope with a different effective shape, the diffraction pattern can be controlled so that the starlight is much dimmer closer to the center in some areas, and brighter in others. The telescope can be rotated about its line-of-sight so that the planet image passes in an out of the regions where the starlight is dim. Coronographic design for planet detection must also concern itself with "wavefront control", the ability to correct for imperfections in the optics, which can scatter light and degrade the all-important image contrast. To correct for its own internal imperfections, such a coronograph would have to use active optics, similar to technology on ground-based telescopes to correct for wavefront distortion in the Earth's atmosphere, though not operating at such a high rate.

Coronographs operating at visible wavelengths have the advantage of requiring a smaller telescope to obtain the required resolution. Their detectors can also operate at room temperature, and require less thermal control than would be needed for a telescope operating the in the thermal infrared.

The Terrestrial Planet Finder Mission

The techniques described above are currently being considered for the design of large planet detection and characterization missions, such as the European Space Agency's Darwin mission, potentially a free-flying infrared interferometer, and NASA's Terrestrial Planet Finder (TPF) mission, for which both architectures above are being studied. For TPF, one of the architectures under study will be selected in 2006, to be then developed for the mission, which will launch in about 2015.

Although the Kepler mission will have given us an idea of how common Earth-sized planets are in our galaxy, it will not have directly, or indirectly, detected any extrasolar planets around the stars in our immediate solar neighbourhood. The primary scientific goal of TPF then, is the direct detection and characterization of Earth-like planets around as many as 150 stars, up to 45 light-years away. In addition to detecting the planets, TPF is being designed to be able to take low-resolution spectra of some of the more interesting candidates, to look for atmospheric and surface signatures that might tell us whether the planet is habitable, or whether it already supports life. In the another chapter, we will discuss how TPF will be able to understand a planet's characteristics, and whether or not it supports life, based only on astronomical measurements.

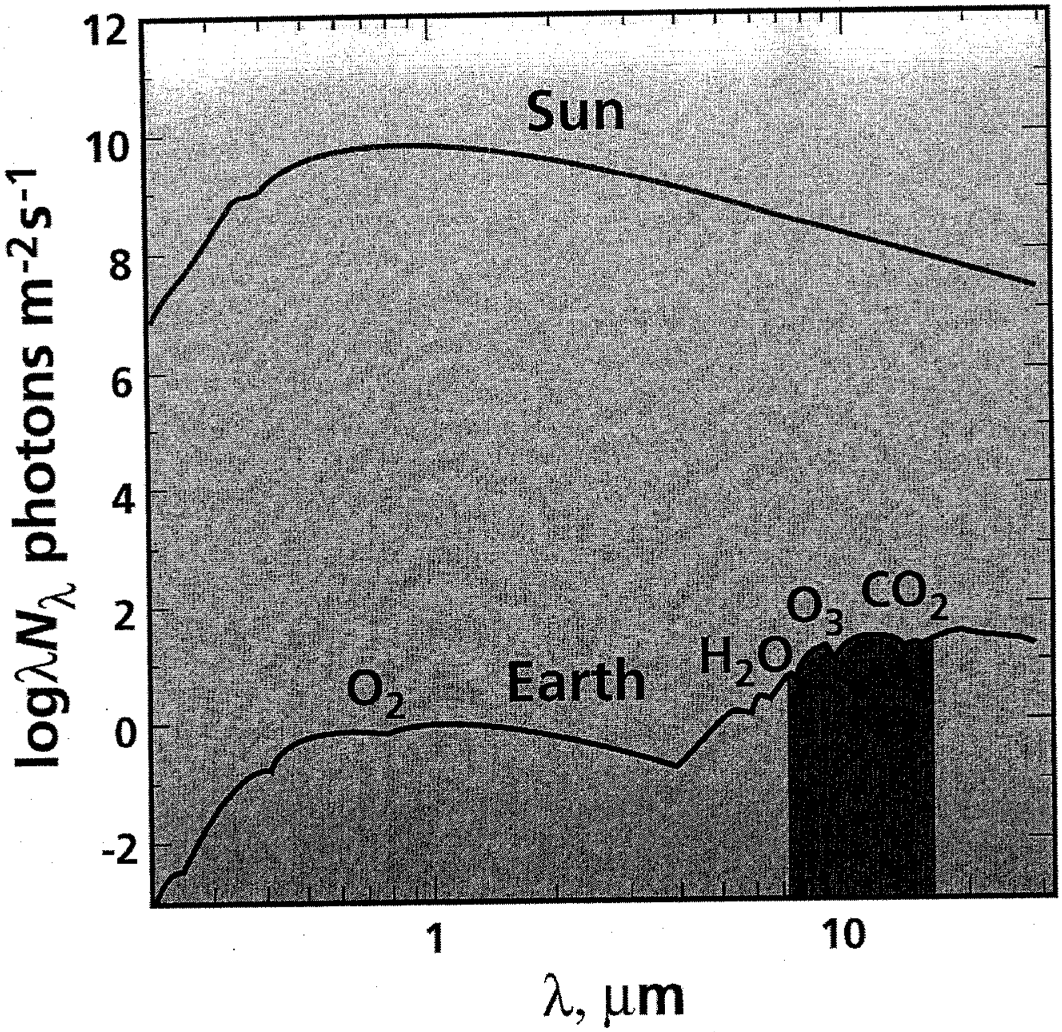
Summary and Conclusion

In this chapter we have reviewed the principal techniques being used or developed to search for extrasolar planets. These techniques fall into two broad categories, indirect and direct. Indirect search techniques, such as the Doppler (radial velocity) technique, astrometry, transits and the use of gravitational microlensing, all rely on changes to the parent star, either position or brightness, to reveal the presence of a planet. In contrast, direct techniques, such as nulling interferometry or coronography, seek to suppress the glare from the parent star, and provide sufficient angular resolution that the tiny, faint planet can be distinguished from its parent star and detected directly. Although most of the indirect techniques are currently in use, the direct techniques are still under development. The direct techniques are enormously technologically challenging, but will enable extrasolar planetary characterization of the closest planets to our Solar System, beyond basic properties such as planet size, mass, and orbital characteristics. In our lifetimes, these techniques will allow us to obtain spectra of nearby extrasolar planets, and finally determine whether, in the words of Giordano Bruno, these countless worlds are "no worse, and no less inhabited than our Earth".

Further Reading

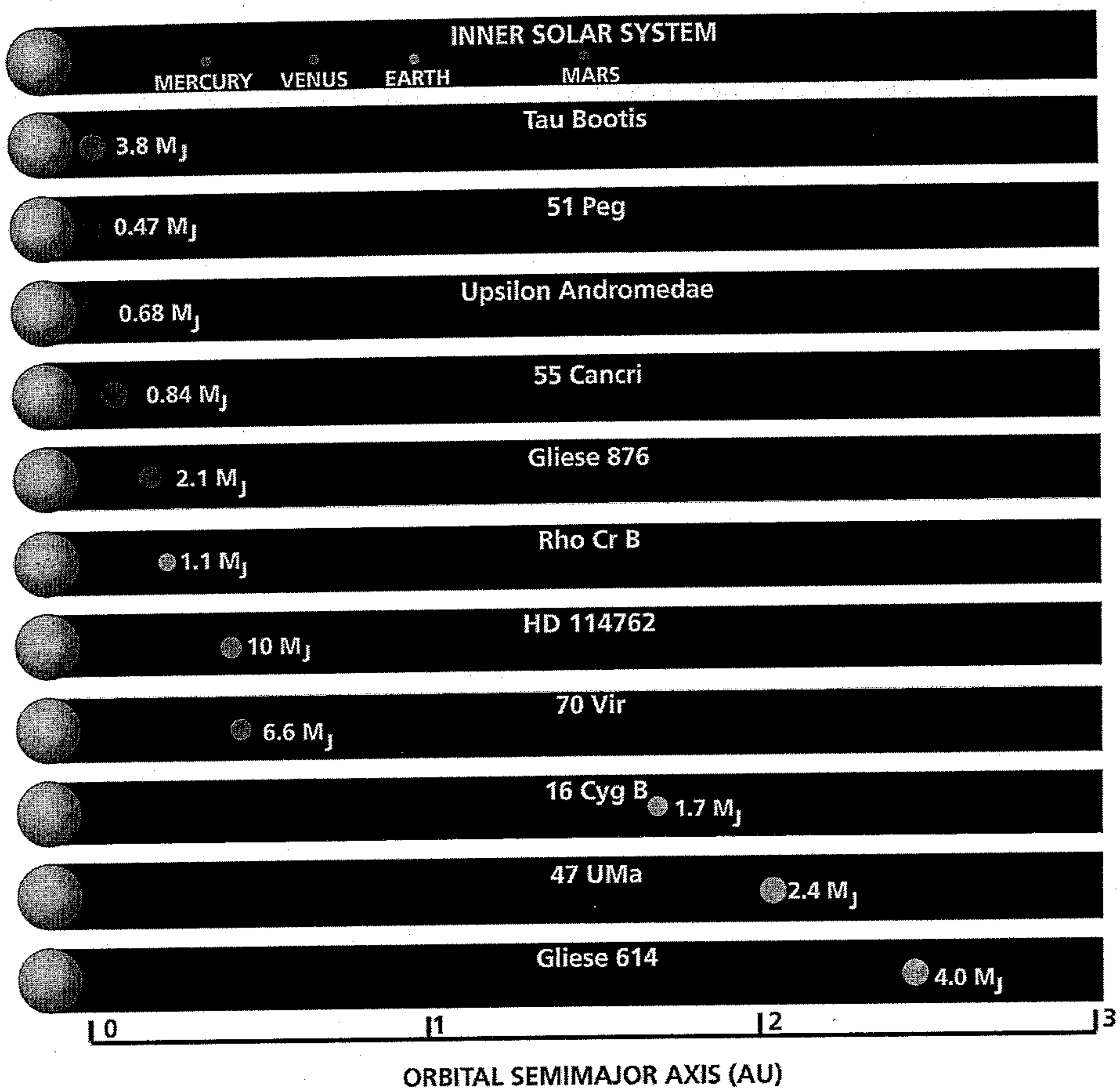
http://planetquest.jpl.nasa.gov/
Looking For Earths: The Race to Find New Solar Systems", by Alan Boss, John Wiley and Sons, 2000.

Fig. 1



12
10
8
6
4
2
0
-2
Sun
Earth
O_2
H_2O
O_3
CO_2
logλN_λ photons $m^{-2}s^{-1}$
1
10
λ, µm

Figure 2



INNER SOLAR SYSTEM
MERCURY
VENUS
EARTH
MARS
Tau Bootis
3.8 M_J
51 Peg
0.47 M_J
Upsilon Andromedae
0.68 M_J
55 Cancri
0.84 M_J
Gliese 876
2.1 M_J
Rho Cr B
1.1 M_J
HD 114762
10 M_J
70 Vir
6.6 M_J
16 Cyg B
1.7 M_J
47 UMa
2.4 M_J
Gliese 614
4.0 M_J
0
1
2
3
ORBITAL SEMIMAJOR AXIS (AU)

Figure 3

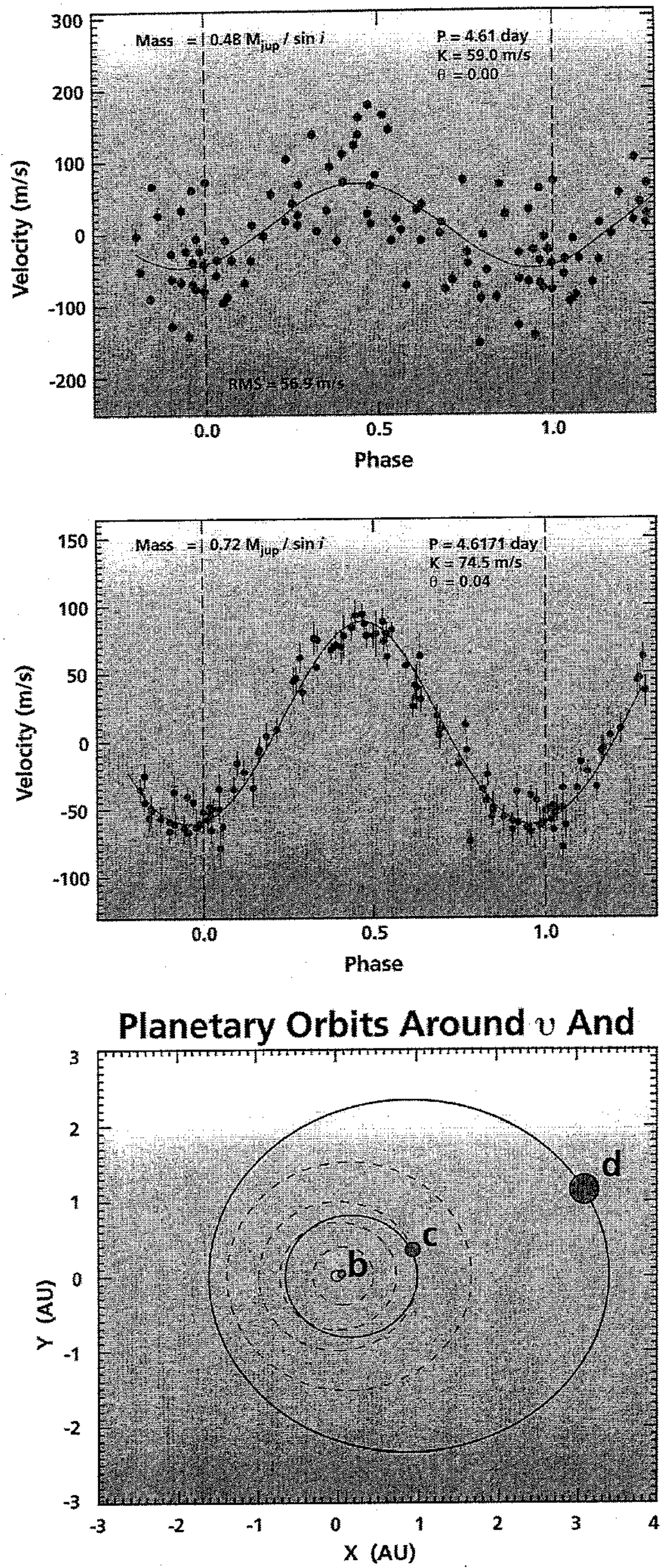

Mass = 0.48 M_jup / sin i
P = 4.61 day
K = 59.0 m/s
θ = 0.00
RMS = 56.9 m/s
Velocity (m/s)
Phase
Mass = 0.72 M_jup / sin i
P = 4.6171 day
K = 74.5 m/s
θ = 0.04
Velocity (m/s)
Phase
Planetary Orbits Around υ And
b
c
d
Y (AU)
X (AU)

Figure 4

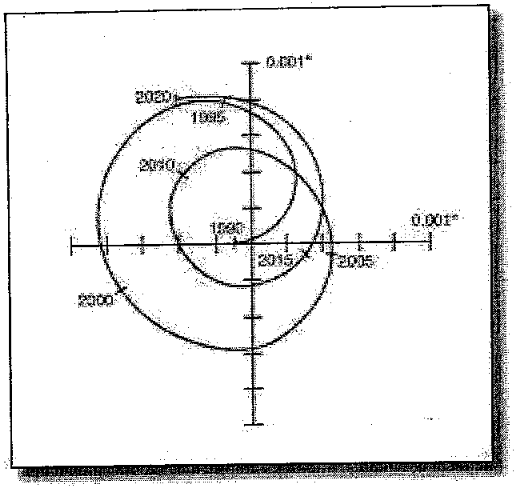


Figure 5

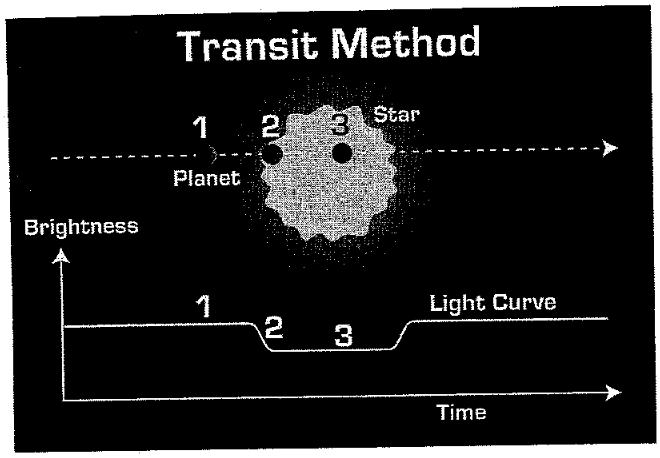

Transit Method
1
2
3
Star
Planet
Brightness
1
2
3
Light Curve
Time

Figure 6

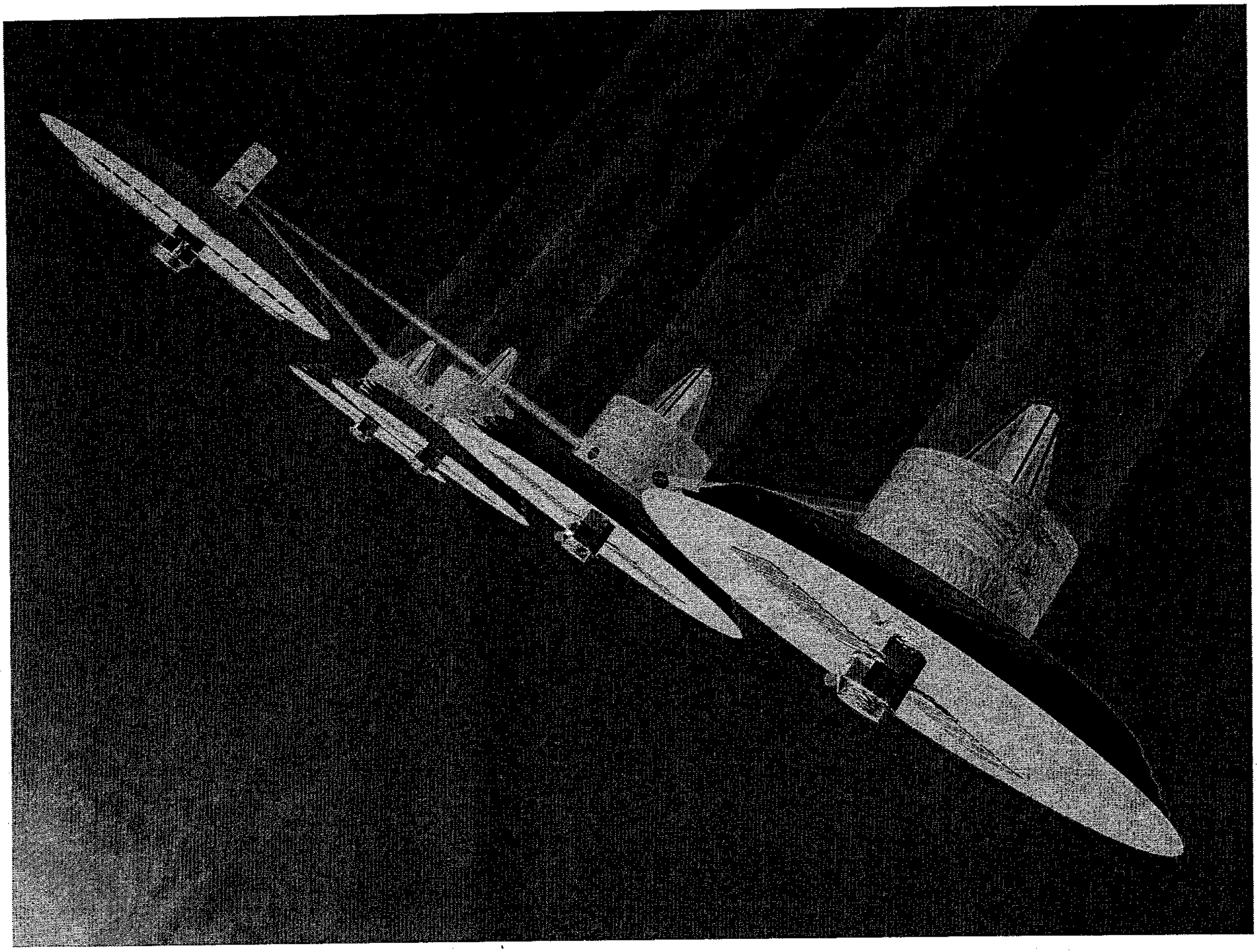


Figure 7