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The Hubble Space Telescope and the Search for Faint Extrasolar Companions

by Andrew J. LePage

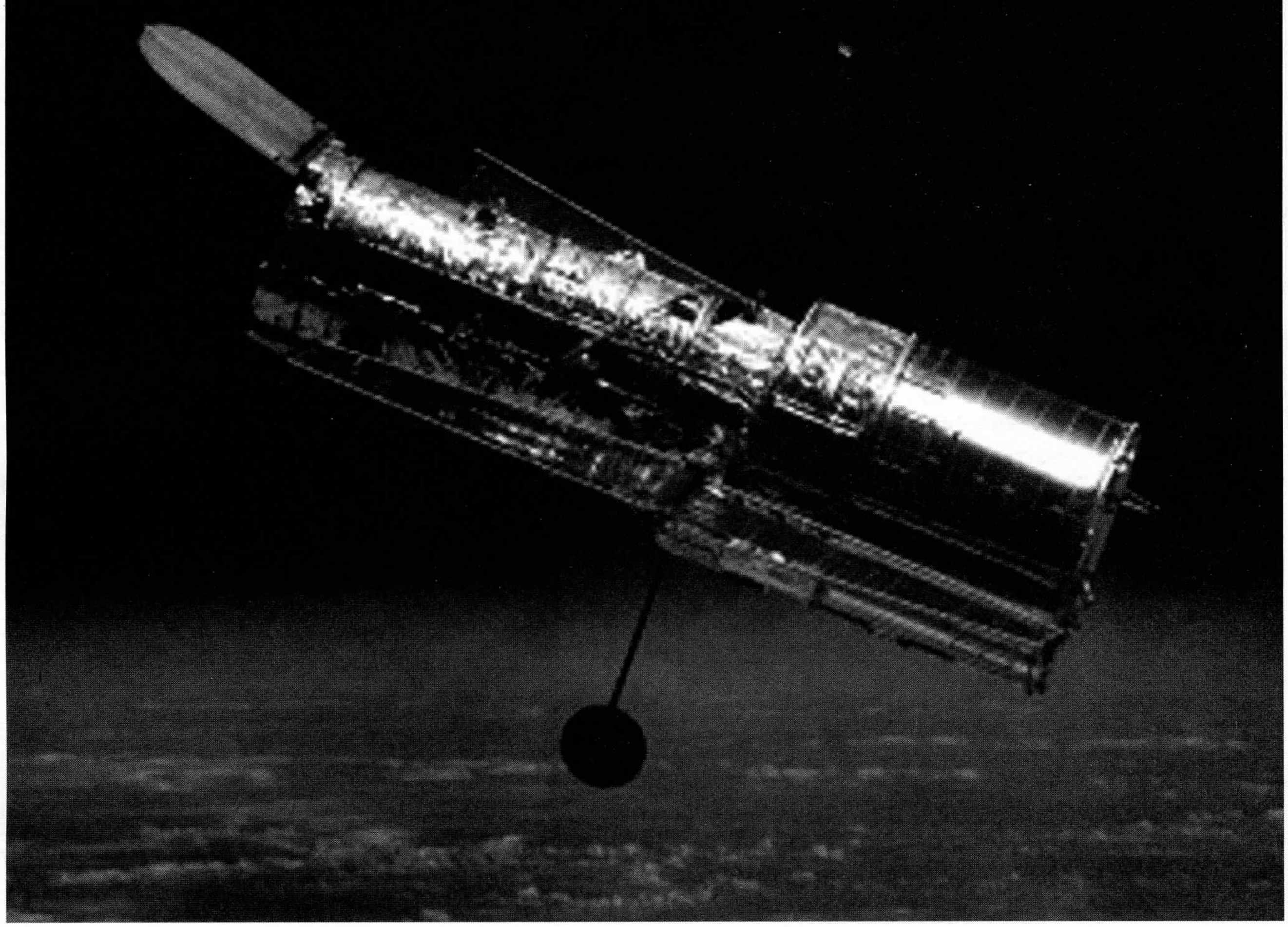

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Figure 1: *Here we see the Hubble Space Telescope after it was released from the space shuttle* Discovery*'s cargo bay. Over the course of several days in late February 1997, it received two new instruments and numerous hardware upgrades. The STS-82 mission was the second regular service mission to the Hubble Space Telescope. The next mission, STS-103, is currently scheduled for 1999.*

Ever since the Copernican Revolution displaced the Earth from the center of the Universe more than four centuries ago, astronomers have openly considered the possibility that the stars in the sky could have planets just as our Sun does. The Dutch astronomer Christian Huygens was the first astronomer known to search for extrasolar planets in the late 17th century with his then state-of-the-art telescope (1). But his attempt and all conventional telescopic searches since have failed to spot a single extrasolar planet. This is because of the extreme difficulty of detecting an object more than 25 magnitudes dimmer than its primary an arc second or less away.

While the presence of extrasolar planets has recently been inferred by such indirect means as radio timings, radial velocity measurements, and astrometry, many astronomers and the public are somewhat skeptical and adhere to the

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Table of Contents

VOLUME 3, NUMBER 2

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philosophy of "seeing is believing." They want to see a picture of an extrasolar planet before they truly believe it.

The best optical telescope currently in operation is undoubtedly the Hubble Space Telescope (HST). Orbiting far above the Earth's atmosphere, its view of the heavens from the near infrared to the ultraviolet is unobstructed by the absorbing effects of ozone, carbon dioxide, water vapor, and other gases. Since COSTAR was installed during the first HST service mission in December of 1993, the HST's diffraction-limited optics regularly obtain the highest angular resolution images available at optical wavelengths. With such superlative performance, the HST offers us our best chance of directly imaging not only planets but other faint extrasolar companions such as brown and red dwarfs until more advanced telescopes become available.

FAINT OBJECT CAMERA

The HST is equipped with a variety of optical instruments to take advantage of its unique capabilities. The first one that would seem to be a logical candidate to search for faint companions is the Faint Object Camera (FOC). Supplied by the European Space Agency (ESA), it was one of the original instruments the HST carried into orbit when it was launched in 1990. This state-of-the-art (at least for the 1970s when it was originally constructed) photon-counting imager is capable of making high-resolution images at wavelengths between 115 and 650 nanometers. With an image scale as small as 14 milliarc seconds per pixel, the FOC has the highest resolution of any instrument carried by the HST and makes the most of Hubble's optical capabilities (2).

In the mid-1980s, Cesare Barbieri and his colleagues from the University of Padua and the ESA proposed using the unique capabilities of the FOC to search for faint companions around a handful of nearby stars including the famous Barnard's Star (3). The initial hopes for the abilities of the HST in this endeavor proved to be overly optimistic even after COSTAR corrected for the HST's primary mirror's spherical aberration. A variety of subtle optical effects such as point spread function (PSF) artifacts and faint ghost images produced by some filters made the detection of very faint planets near their much brighter primary very difficult. Practical limitations with the detector and its digital electronics as well as onboard memory make it virtually impossible to take enough digital images to detect the very faintest companions of our stellar neighbors. Because of the sensitivity of the FOC, there are also safety limitations that prohibit making observations near bright stars (2).

This is not to say that the search for faint extrasolar companions using the FOC was fruitless. As long as the companion is not too much dimmer than its primary, the FOC can observe it. As a result the FOC has been used to search for faint stellar companions of a few dim nearby stars. In June of 1994 Barbieri's search detected a faint **V** magnitude 16 companion orbiting only 2 AU from GL 623 (4). GL 623 itself is a faint M2 dwarf star 24 light years from the Earth. Its small stellar companion with a mass of only 0.1 $M_{\odot}$ (100 $M_{♃}$) had been previously detected only from ground-based astrometric observations. While it is not a planet or even a brown dwarf, this was the first optical detection of Gl 623B and these observations will lead to a better understanding of the formation of small stars.

WIDE FIELD PLANETARY CAMERA 2

Another important feature designed into the HST was the ability to change instruments in orbit during regularly scheduled service missions. The first instrument to be so replaced was the Wide Field Planetary Camera (WFPC). Its replacement, the improved WFPC-2, incorporated the latest large-format CCD imaging array technology and a set of built-in optics to correct for the HST's unintended nearsightedness. The detector consists of three 800 by 800 pixel CCD detector arrays arranged to produce an L-shaped image with a scale of about 100 milliarc seconds per pixel. Nestled in the inner corner of this array is a single 800 by 800 pixel CCD with a higher resolution 46 milliarc seconds per pixel image scale (5). While WFPC-2 does not have the resolution of the FOC, it does have superior sensitivity at wavelengths longer than 400 nanometers and is not severely encumbered by target brightness constraints. In fact, WFPC-2 has very high sensitivity out to wavelengths as long as one micron where young and massive brown dwarfs would be the brightest. Early studies also indicated that planetary detection could be possible (6).

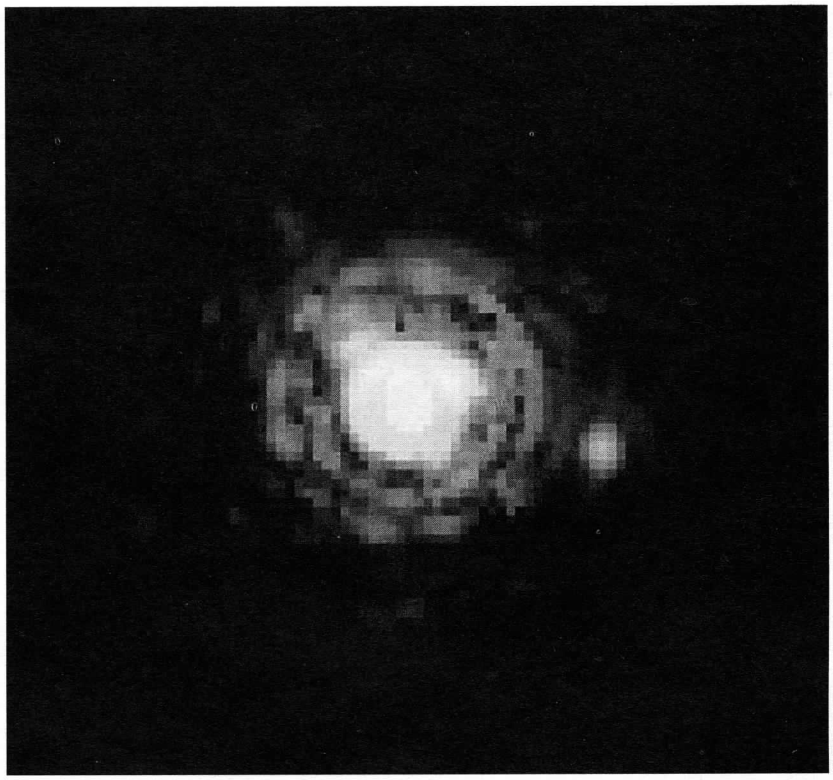


PHOTO COURTESY OF C. BARBIERI (UNIVERSITY OF PADUA) AND NASA / ESA

Figure 2: *This is an image of GL 623 and its faint companion as imaged on June 11, 1994, by the Faint Object Camera. This faint extrasolar companion was first detected indirectly by ground-based astrometry but it was too dim and close to its primary to be seen from the ground. This image clearly shows GL 623B among the diffraction rings of the image of its primary.*

As with the FOC, the hope of seeing very dim objects near bright stars proved to be overly optimistic. Using prelaunch measurements to estimate the HST's PSF, more detailed follow-up studies showed that the glare from the star would overwhelm the image of a nearby planet (7). Despite this instrument's limitations, faint brown and red dwarfs could be spotted and William Fastie and Daniel Schroeder planned to start a search of nearby stars shortly after the launch of the HST. After the problems with the HST's optics were discovered during its post-launch checkout, this search had to be postponed until the HST's optics could be corrected.

Since WFPC-2 was installed during the first service mission in December 1993, a series of tests were performed to characterize the performance of the HST and WFPC-2. Using these results, Schroeder and David Golimowski performed a detailed empirical study of the ability of WFPC-2 to detect faint extrasolar companions (8). They discovered that azimuthal variations in the instrument's PSF were 10 to 20 times larger than expected from a perfect PSF. In addition, the PSF varied slightly from place to place in the field of view. These effects are thought to be due to light scattering nonuniformly from the surface of the detector. This problem makes it impossible to precisely model a star's PSF well enough so that it can be subtracted to reveal its faintest companions. With these effects present, 180 images taken over ten orbits would be required to obtain a 10σ detection of a Jupiter circling the nearest sun-like stars (8). Given the limitations of onboard memory and the demands for time on HST from the rest of the astronomical community, a comprehensive search for Jupiter-like planets is impractical.

Using more realistic demands of the HST's performance and observing time, a search of 18 nearby stars was started in an effort to spot any relatively young and bright brown dwarfs as well as the dimmest red dwarfs more than an arc second from these stars. Estimates indicate that a brown dwarf as dim as **I** magnitude 16.7 could be spotted one arc second (about 1.3 AU) from α Centauri A (8). So far this search has made one find: A faint M7V star orbiting GL 105A approximately every 60 years. GL 105A is a K3V star about 23 light years away. A low mass, borderline stellar companion in the 0.80 to 0.140 $M_\odot$ (84 to 147 $M_♃$) mass range had been suspected to exist based on astrometric measurements (9). Golimowski and his associates first spotted the new companion using the Palomar Observatory 60-inch telescope (10). With an **I** magnitude of 13.5 and a separation of 3.4 arc seconds, GL 105C was easily spotted by WFPC-2. No other objects with an **I** magnitude greater than 20.3 was spotted between 1 and 13.5 arc seconds (about 7 to 100 AU) from GL 105A (11).

Although not on the original survey list, WFPC-2 has already been used to image the first known brown dwarf

PHOTO COURTESY OF S. KULKARNI (CALTECH), D. GOLIMOWSKI (JOHNS HOPKINS UNIVERSITY), AND NASA

Figure 3: *The Wide Field Planetary Camera 2, which was installed during the first service mission to the Hubble Space Telescope in December 1993, confirmed the ground-based detection of the first known brown dwarf, GL 293B, with this image taken on November 17, 1995. The Wide Field Planetary Camera 2 is being used for a survey of 18 nearby stars looking for faint companions.*

circling Gl 229. Initially detected during the same Palomar Observatory search program that spotted GL 105C (12), the HST would make it possible to confirm this unique object's existence. With an **I** magnitude of 20 and a wide separation of 7.8 arc seconds, this young brown dwarf was easily detected by WFPC-2 and its observations have proved valuable in confirming this object's substellar nature (13).

FAINT OBJECT SPECTROGRAPH

One of the major problems in using the previous two imaging instruments to search for faint companions is the brightness of the primary. The FOC could be permanently damaged observing a bright target. While WFPC-2 is less prone to damage, charge overflow out of the pixels of an overexposed bright target corrupts large portions of its images. What is needed is a coronagraph to block out the majority of the light from the primary star so that any faint companions can be more easily observed. Until recently, the only HST instrument with a coronagraphic capability was not an imager but a spectrometer.

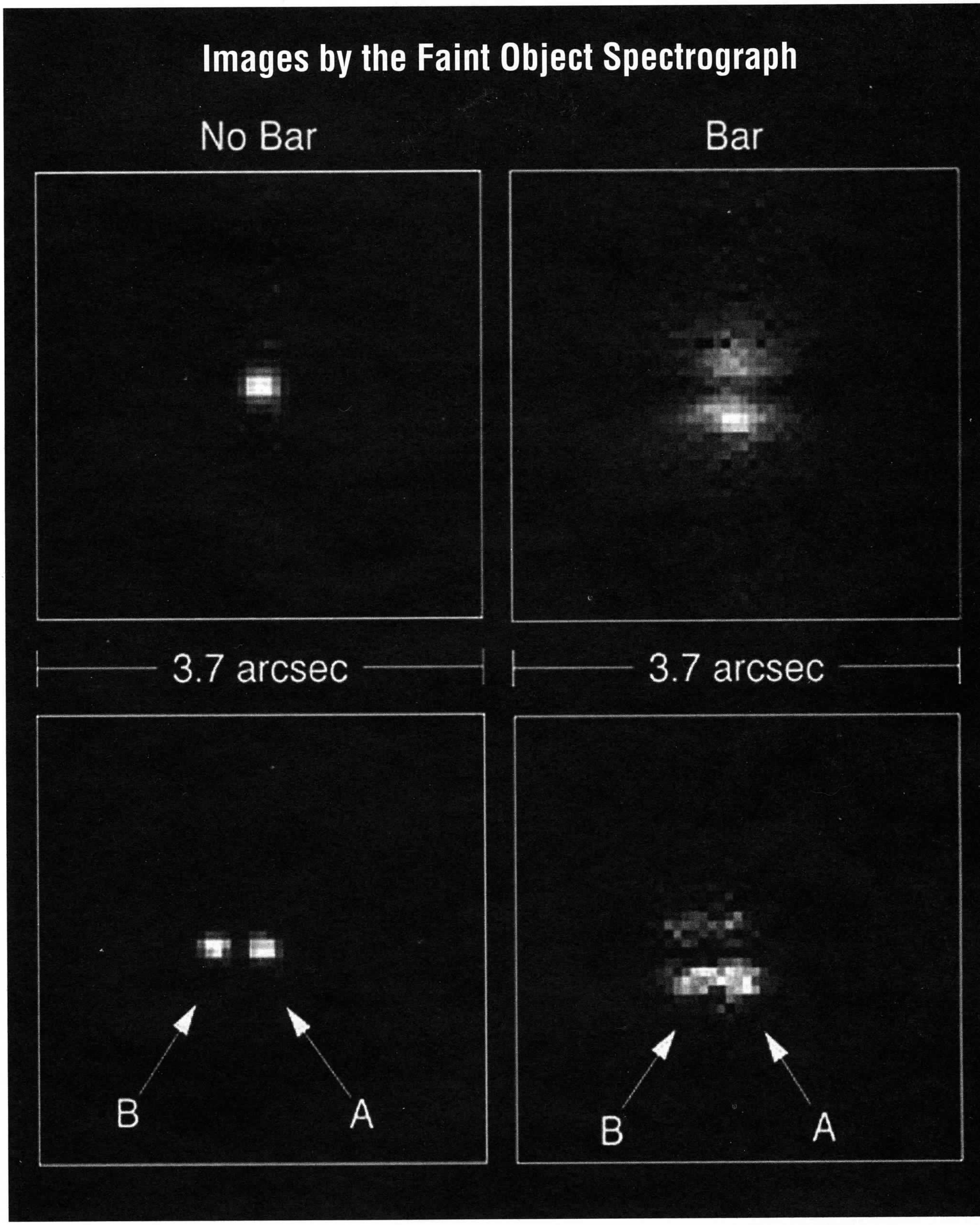
The Faint Object Spectrograph (FOS) is equipped with a variety of apertures including one called 2.0-BAR which consists of a 1.71 arc second square aperture with a 0.27 arc second wide occulting bar in its center (14). The intent of this aperture was to block the light coming from a bright object so that a spectrum of a faint nearby object could be obtained.

Although the FOS was not designed to take images in the conventional sense, it does have a mode of operation that allows it to produce crude pictures. In this mode called ACQIMAGE, the FOS's pointing mirror directly images its aperture onto Digicon detectors which consists of a linear array of 512 rectangular-shaped diodes. By stepping the mirror four times in the X direction and 20 times in the Y, spatial brightness data from a 3.7 arc second field of view can be obtained. Applying sophisticated Fourier processing techniques to the data yields an image with a scale of about 80 milliarc seconds per pixel (15). Although the final image contains some processing artifacts and might not be very pretty, the coronagraphic capability of the FOS combined with the high sensitivity and dynamic range of its Digicon detectors makes possible very sensitive searches for companions as faint as **V** magnitude 23.

A team of astronomers have made use of this technique to search for faint companions around a limited number of nearby stars. Among the first observations to be made were of the system GJ 1245AC. This system is composed of a pair of faint M dwarf stars 14.8 light years from us and about a half an arc second apart from each other. The FOS images were easily able to resolve the components of this system (16). These images indicate that the smaller member of this system is closer to its primary than suspected earlier. This means its mass is smaller than the earlier estimated 0.085 $M_{\odot}$ (89 $M_{♃}$) making it a likely brown dwarf candidate. No other faint nearby companions were found in the search of this system.

The FOS also spied what could be another brown dwarf in the Wolf 424 system (17). This system is only 14.0 light years away and is composed of a pair of closely orbiting bodies with a total **V** magnitude of 12.5. Ground-based observations had led to a total estimated mass of 0.110 $M_{\odot}$ (115 $M_{♃}$) for this system making it possible that both components were substellar in nature. The HST's observation in 1996 measured the position of the two components when they were separated by only 0.41 arc seconds. Combined with ground-based infrared speckle imaging and earlier observations, it was concluded that this system's orbit needs to be updated. It now appears that the total mass is around 0.142 $M_{\odot}$ (149 $M_{♃}$). It still is quite likely that at least one of these two objects is a brown dwarf. While the presence of both of these objects had been expected from ground-based observations, the new FOS images did not reveal the presence of any other faint companions within 8 AU.

To date, the FOS has searched a total of four nearby systems for faint companions. The other two systems included Wolf 359 and GL 293. Wolf 359 is an M dwarf only 7.5 light years away making it the third closest star system known (after the α Centauri triple system and Barnard's Star) (15). GL 293 is a faint white dwarf star 18.8 light years away. Past ground-based imaging and astrometry had



PHOTOS COURTESY OF H. HART & A. SCHULTZ (COMPUTER SCIENCES CORP.), F. BRUHWEILER (CATHOLIC UNIVERSITY OF AMERICA), THE HST FOS IMAGING TEAM, AND NASA

Figure 4: *These images were reconstructed from data taken by the Faint Object Spectrograph while in the ACQIMAGE mode. The images at the top show the nearby star called Wolf 359 while the bottom pair show the Wolf 459 system composed of two dim objects that lie very close to the border between red and brown dwarfs. The images on the left were taken without the occulting bar in place and easily show the known components of these systems. The pair of images on the right were obtained in a coronagraphic mode where the bright components are hidden behind a 0.27 arc second wide occulting bar. These long coronagraphic exposures show no signs of other faint companions. All that can be seen are the faint wings of the known stars' point spread functions leaking from behind the occulting bar.*

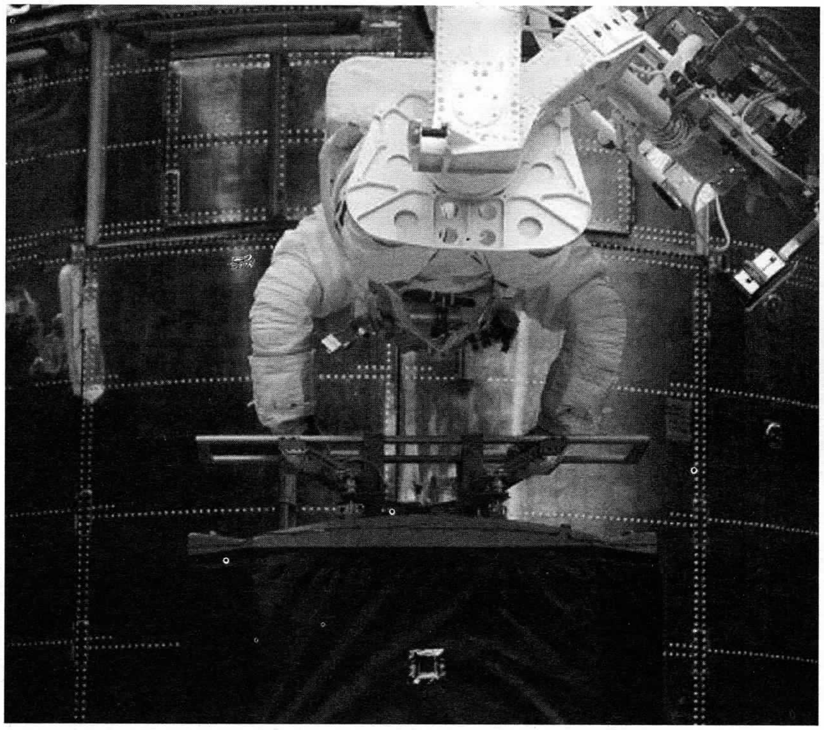


Figure 5: *Shown here is a new Fine Guidance Sensor in the* Discovery *cargo bay being prepared for installation in the Hubble Space Telescope during the STS-82 service mission. FGS #3 has been used to perform precision astrometry in the hopes of indirectly detecting Jupiter-sized planets orbiting the two closest known red dwarf stars, Proxima Centauri and Barnard's Star.*

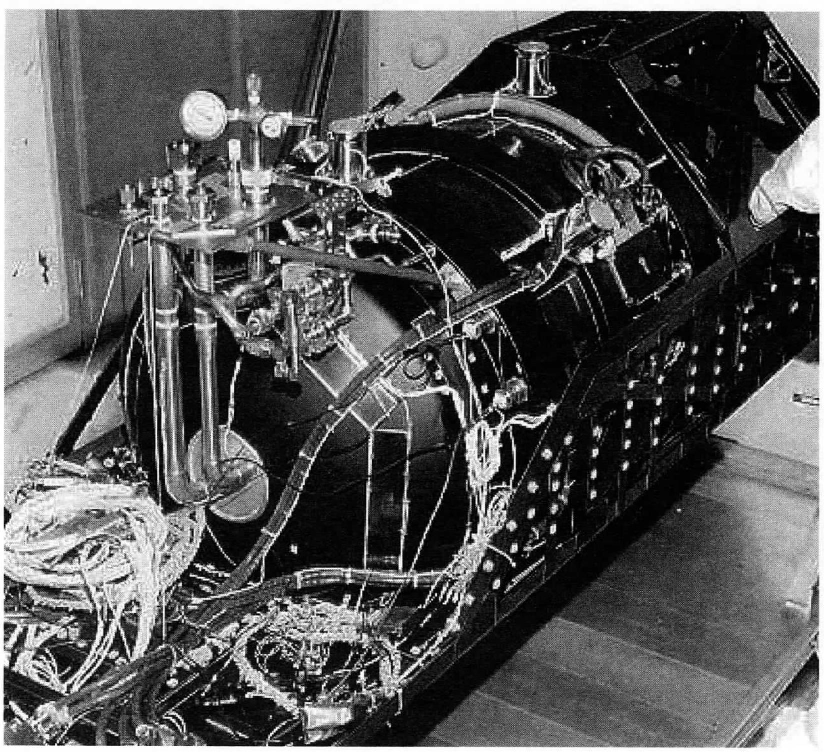


Figure 6: *Shown here is the Near Infrared Camera and Multi-Object Spectrometer (NICMOS) during the integration of its cryogenic dewar and optical truss. This new instrument was installed during the second service mission to the Hubble Space Telescope and has the best chance of spotting another Jupiter orbiting a nearby star.*

failed to detect any companions around either of these two stars. FOS's new images nicely complemented these previous observations pushing the search closer to the primaries and to dimmer magnitudes (16). The FOS failed to detect any previously unknown faint companions close to either star.

FINE GUIDANCE SENSOR

The HST's Fine Guidance Sensors (FGS) are white light Koester prism interferometers used to keep the HST locked in position while its other instruments take data (18). They perform this job by precisely measuring the position of selected guide stars during an observation session. While HST's three FGS units are not imaging instruments, it was recognized quite early on that they could be used to perform astrometry with a single observation precision of about 3 milliarc seconds (19). Averaging many observations makes FGS capable of making measurements with a precision of 1.5 milliarc seconds or better. This makes it possible to use a FGS to measure the proper motions and parallaxes of stars with a precision that has only recently been equaled using specialized ground-based instruments. This capability also makes the astrometric detection of unseen companions possible. For the smallest and closest M dwarf stars, the detection of Jupiter-sized planets is theoretically possible. With this capability in mind, FGS #3 was fitted with a broadband visible light filter specifically designed to make astrometric observations (18).

G. Fritz Benedict of the McDonald Observatory and his colleagues have used the capability of FGS #3 to precisely measure the motions of a handful of M dwarf stars in order to obtain more accurate orbits for their known or suspected companions. FGS #3 has also been used to search for planets around the two closest M dwarf stars: Proxima Centauri and Barnard's Star. Using preliminary data, Benedict announced that his team's measurements had detected an unaccounted-for wobble that could indicate the presence of a 0.9 $M_{♃}$ planet in an 80-day orbit (20). Subsequent observations and analysis makes this interpretation increasingly unlikely. Photometric observations indicate that Proxima Centauri has a rotational period that is also 80 days long (21) hinting that part of the observed wobble could be the result of unresolved bright spots moving across the face of this known flare star. Follow-up radial velocity measurements from the ground performed by the ESOPS team at the European Southern Observatory have turned up inconclusive evidence for the possible presence of this planet (22).

Detailed analysis of the FGS data from Proxima Centauri and Barnard's Star indicate that there are also systematic errors of an unknown source remaining in the data. When all known sources of error are taken into account, FGS astrometric measurements should be able to detect a planet around Proxima Centauri or Barnard's Star with a mass of at least 1 $M_{♃}$ in orbits with a period between 90 and 600 days (i.e., with orbits between about 0.2 to 0.7 AU).

To date no planet has been found orbiting either star with these parameters (23). The results to date for Barnard's Star do confirm the precision ground-based astrometry performed by George Gatewood of the Allegheny Observatory using the Multichannel Astrometric Photometer (24). Additional data and analysis should be able to remove the remaining systematic errors and extend the search, making possible the detection of Saturn-sized planets in more distant orbits. During the STS-82 service mission in February 1997, one of the FGS units was replaced. Early estimates of its capabilities make it likely that its performance will be slightly better than FGS #3 for astrometric measurements making still smaller planets detectable (18).

NEXT GENERATION OF INSTRUMENTS

More than just a FGS was replaced during the most recent HST servicing mission. The FOS described above and the Goddard High Resolution Spectrograph were also replaced with two new instruments built by Ball Aerospace which incorporate the latest detector technology. The first is the Near Infrared Camera and Multi-Object Spectrometer (NICMOS). Actually NICMOS consists of three low-noise, high-quantum efficiency 256 by 256 pixel mercury cadmium telluride (HgCdTe) detector arrays cooled by a block of solid nitrogen (25). Each camera is designed with different pixel scales as well as complementary filters and special features. These detectors are sensitive to wavelengths ranging from 0.8 to 2.5 microns but have peak efficiency in the 1.1 and 1.6 microns range. Longward of 0.9 microns, NICMOS is more sensitive than WFPC-2. At these near infrared wavelengths, the heat radiating from brown dwarfs and young extrasolar giant planets is most visible. In fact, detailed simulations performed by Adam Burrows of the University of Arizona and his colleagues indicate that NICMOS is sensitive enough to detect the reflected light from Jupiter orbiting the Sun as far as ten parsecs away (26).

Of the three cameras, the one that will likely have the best chance of spotting another Jupiter is designated NIC2. This camera has a field of view 19.2 arc seconds on a side yielding an image scale of 75 milliarc seconds per pixel. In theory it is capable of detecting a **J** magnitude 25.7 object after a one-hour exposure (25). What makes this camera well-suited for detecting extrasolar giant planets (EGP) is its coronagraphic imaging mode. A precision 170 micron in diameter hole was laser ablated out of NIC2's mirror in NICMOS's field divider assembly where light from the HST optics is directed to the three cameras. The hole creates an occulting spot with a radius of 300 milliarc seconds. This is the precise size of the primary peak of an ideal PSF at 1.6 microns. In theory, 93 percent of the light from the primary star is blocked by the occulting spot.

In addition to light coming directly from the primary star, scattered light must also be minimized to suppress background noise. To help do this, an oversized cryogenic pupil-plane mask screens out residual radiation from the HST's secondary mirror support structure as well as about 15 percent of the primary mirror area (25). In-orbit calibration and testing will be required to characterize the effects of scattered light as well as the accuracy with which a star can be centered behind the occulting spot. These tests will have to be completed before a definitive statement can be made about NICMOS's chances of detecting another Jupiter orbiting a nearby Sun-like star. Simulations to date indicate that EGPs orbiting at about 5 AU are most likely to be seen around relatively nearby and bright stars like Vega, τ Ceti, and ε Eridani (27). These same simulations predict that NICMOS does not have the sensitivity to detect any

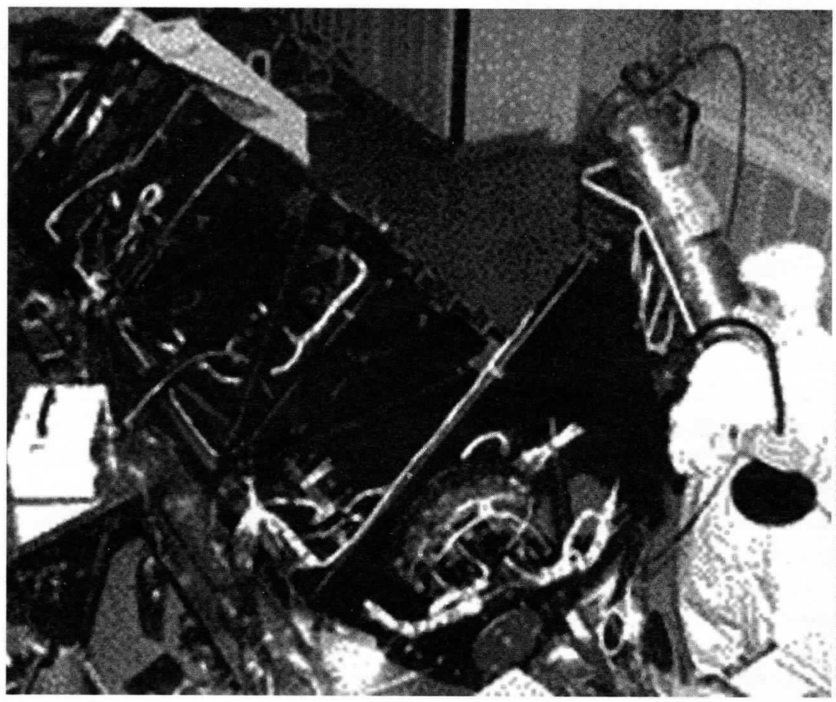


PHOTO COURTESY OF BALL AEROSPACE CORPORATION

Figure 7: *The Space Telescope Imaging Spectrometer is probably the most sophisticated instrument launched into space. It was installed in the Hubble Space Telescope during the second service mission and will take on the spectrographic responsibilities of the Faint Object Spectrograph and the Goddard High Resolution Spectrograph that were removed during this same mission. The Space Telescope Imaging Spectrometer should be capable of obtaining spectra of relatively bright brown dwarfs and should be capable of detecting extrasolar giant planets of bright nearby stars in its imaging mode.*

PHOTO COURTESY OF JOHNS HOPKINS UNIVERSITY

Figure 8: *This is an optical bench mockup of the Advance Camera for Surveys that will be installed in the Hubble Space Telescope during the third service mission scheduled for 1999. It will have more advanced detectors than Wide Field Planetary Camera 2 and a coronagraphic capability. It should be capable of making efficient searches for and observations of faint companions in visible wavelengths.*

extrasolar giant planets (EGP) that might orbit nearby red dwarf stars like the famous Barnard's Star. Much larger ground-based telescopes operating at longer wavelengths will be needed to do that any time in the near future.

Another NICMOS camera has a capability that could prove useful in examining moderately bright brown dwarfs in our stellar neighborhood. NIC3, with a 51.2 arc second field of view and an image scale of 200 milliarc seconds per pixel, is equipped with a set of three "grisms"—a combination of prism and diffraction grating—to perform slitless spectroscopy in three overlapping infrared wavelength bands (25). With a resolving power of 200, it should be able to obtain useful spectra of objects brighter than about **J** magnitude 20 or **K** magnitude 17. It could easily obtain data for the brown dwarf GL 293B free of our atmosphere's infrared absorption bands that have hampered ground-based studies of this object. It might also be possible for NIC3, in its spectrographic mode, to detect young and bright EGPs closely orbiting the bright star Vega at wavelengths near one micron. Again, detailed in-orbit testing will be needed to assess this capability.

The other new instrument added during the most recent service mission was the Space Telescope Imaging Spectrometer (STIS). This instrument makes use of three different detectors to perform high-resolution spectroscopy at wavelengths from 115 nanometers in the ultraviolet to about one micron in the near infrared. The ultraviolet capability will be of little use in searching for or studying faint extrasolar companions which tend to be brighter in the infrared. The STIS's 1024 by 1024 pixel CCD array, which is sensitive to wavelengths as long as 1.1 microns, has the most to offer in the study of faint companions (28). This spectrometer should be capable of obtaining useful spectra of objects as dim as **V** magnitude 21 with a one-hour exposure. It also has an aperture available with a 400 milliarc second wide occulting bar that can be used to block the light from a bright primary. There is little chance that this instrument will be able to study EGPs but it should perform well in the study of faint red and brown dwarfs.

The STIS also has an imaging capability available that in some ways is superior to that offered by WFPC-2 due to STIS's newer detector technology and a broadband filter. In the clear imaging mode, the CCD imager has a 50 arc second square field of view and a 50 milliarc seconds per pixel image scale. A one-hour exposure through the clear filter should be capable of imaging objects as faint as **V** magnitude 28 (28). In the imaging mode there is also a special coronagraphic aperture available with one 3 by 10 arc second occulting bar and two intersecting 50 arc second long occulting wedges varying from 0.5 to 3.0 arc seconds in width. Limited apodization via a lyot stop that masks the instrument's exit pupil helps to reduce the effects of scattered light. This capability will be quite useful in searching for faint companions at visible wavelengths. Depending on the results of in-orbit calibration and testing, the STIS may be able to detect Jupiter-sized planets around the closest bright nearby stars.

FUTURE INSTRUMENTS

At least two more servicing missions are planned for the HST during the remainder of its life in orbit. The next mission will be STS-103 which is currently scheduled for launch in 1999. It is slated to carry the Advance Camera for Surveys presently under development at Johns Hopkins University. This instrument will consist of three CCD detector arrays with complementary capabilities. The High Resolution Camera appears to be the best suited for the search for faint extrasolar companions. Its detector will be a 1024 by 1024 pixel CCD array that will be sensitive to wavelengths from 200 to 1000 nanometers (29). It will have an image scale of 25 milliarc seconds per pixel and will be equipped with two coronagraphic modes so that faint objects can be more easily seen near bright stars. The instruments that will be brought up during the following service mission in 2003 have yet to be chosen but the ESA will most likely supply one.

With its new suite of instruments and more advanced ones incorporating the latest detector technology being designed, the HST will remain the best telescope for directly imaging faint extrasolar companions and even planets for the next few years. Only after the next generation of ground- and space-based telescopes come into operation over the course of the coming decade will better instruments be available for planetary search programs. In the meantime, the HST should begin to provide our first look at the nature of the planetary systems that adorn our nearest stellar neighbors.

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