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HST: THE ASTRONOMY REVOLUTION

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• INTRODUCTION

The Hubble Space Telescope is the flagship of a growing fleet of modern astronomical telescopes. The unique power of the HST derives from its combination of extremely sharp images, covering relatively wide angular fields in the sky, with a deep dynamic range, low background noise and sensitivity to wavelengths from the vacuum ultraviolet to the near-infrared. HST great contribution has been the facility with which it has converted so many hypotheses, into demonstrated facts. But probably the HSTs greatest achievement is that while providing a detailed view of the unimagined complexity and diversity of the universe, it has yielded numerous surprises and raised new questions. With each new instrument inserted by the astronauts on servicing missions, the HST grows in capability by factors of 10. With the installation of ever more advanced scientific instruments it is likely that the HST's second decade will be even more productive and paradigm changing. The following represent my personal view of the ten most important discoveries of the HST during its first decade of operations.

• IMAGING THE DISTANT UNIVERSE

The HST has provided the first deep, clear view of the distant universe. Only the COBE satellite has probed farther back in time, measuring the radiation left over from the Big Bang itself. The HST has shown that, when the universe was very young, it was populated by structures that were much smaller and much more irregular in shape than the galaxies we see in the modern universe. These smaller structures, made up of young stars and primordial gas, are believed to be the building blocks from which the more familiar spiral and elliptical galaxies were formed. However, the processes involved were complex, involving multiple galaxy collisions, infall of intergalactic gas, and the gravitational influence of supermassive black holes.

• PRECISE CALIBRATION OF THE DISTANCE SCALE

The HST was the first telescope capable of resolving the "standard candle" Cepheid variable stars and using them to obtain very accurate distances to a large number of moderately distant galaxies. These distances were used in turn to recalibrate a number of other standard distance indicators such as Type Ia supernovae, which were applied in extending distance measurements to galaxies at much greater distances out into the "the Hubble flow". The result is a much more accurate measure of the rate at which the universe is expanding (the Hubble Constant) and a determination that the universe is younger than many astronomers had believed it to be; 12-14 billion years have elapsed since the Big Bang.

• MEASURING THE COSMOLOGICAL CONSTANT

In its first decade the HST partnered with ground-based telescopes in searching for and measuring the brightnesses of Type Ia supernovae in distant galaxies whose light was emitted when the universe was about half its present age (redshifts up to Z = 1.2). The HST's major contribution was the accurate measurement of the brightnesses of the most distant supernovae in this sample. From these measurements the galaxies' distances could be accurately determined and these values, combined with their measured recessional velocities, indicated the rate at which the universe itself was expanding far back in time. The result was remarkable, providing the first tentative clue that the expansion of the universe is accelerating – driven by an unknown repulsive "force" strong enough to overcome gravity. Einstein anticipated this possibility by adding a "cosmological constant" to his equations of general relativity. The HST will lead the way in the next few years in extending these measurements even farther across the universe and farther back in time.

• DETECTION AND MEASUREMENT OF SUPERMASSIVE BLACK HOLES

Prior to the launch of the HST, ground-based images of galactic nuclei hinted at the existence of large concentrations of mass at the very centers of galaxies. Although it was suspected that these might be the massive black holes predicted theoretically as early as the 1930's, this was impossible to prove at the resolution of ground-based optical telescopes. The HST was the first optical telescope capable of probing sufficiently close to the center of a galaxy to measure spectroscopically the velocity of stars and gas in orbit around the central concentration and to measure accurately by direct imaging the size of the central cusp of starlight. This provided the first convincing proof of the existence of a central black hole several billion times the mass of the sun. At about the same time a ground- based microwave telescope measured the velocity of water masers in orbit around a black hole of several million solar masses in a different galaxy, thus providing further proof. The HST has now moved beyond the initial confirmation of the existence of supermassive black holes to a demographic survey of central black holes. The HST has demonstrated that these powerful, enigmatic objects are found in the nuclei of most (or perhaps all) galaxies, whether or not those nuclei are energetically active. Ultimately, the HST will help establish the role these "monsters" play in the formation and evolution of galaxies.

• THE NATURE OF QUASARS

For several decades Quasars (quasi-stellar radio sources), sometimes called QSO's (quasi-stellar objects), were among the most enigmatic objects in the universe. They were recognized at the time of their discovery in the 1960's as the most distant and energetic objects known. Continued study suggested a possible relationship between the quasars and another puzzling phenomenon the highly active and energetic nuclei of certain galaxies at more moderate distances, the AGN (for Active Galactic Nuclei). The detection of a very faint "fuzz" around some quasars seen with ground-based telescopes supported the hypothesis that they might be very distant AGN's in the early universe, undergoing especially intense outbursts of activity. The HST has completely verified this idea. The telescope's resolution and dynamic range clearly reveals a variety of underlying host galaxies of quasars. A more surprising HST discovery is that a large fraction of quasar host galaxies appear to be in the process of colliding and merging with other galaxies. This suggests that galaxy collisions, which the HST has shown to be common in the early universe, may have provided the extra "fuel", feeding a massive central black hole in a host galaxy, needed to generate the prodigious energy output unique to quasars.

• THE ORIGIN OF GAMMA RAY BURSTS

Intense bursts of highly energetic gamma radiation from unknown cosmic sources were first detected by military satellites. Thousands of these bursts were subsequently observed by the Compton Gamma Ray Observatory, which found that they were distributed more or less uniformly over the sky. Not only was the source of the bursts a mystery, it was not even known if they originated in our own galaxy, far across the universe, or somewhere in between. The joint Italian-Dutch satellite Beppo-Sax was designed to spot gamma ray bursts very quickly and to locate their positions accurately, so that other telescopes could be trained on them while they were still bright. Using such "alerts" from Beppo-Sax, ground-based telescopes then located the gamma-ray sources in optical-wavelength light. Using this information, astronomers trained the HST on the optical counterparts of multiple gamma ray bursts. The HST's resolution and sensitivity gave it the unique ability to show that the sources of the gamma ray bursts were embedded in faint, distant galaxies at random distances from their centers. By following the brightness changes in the sources to very faint levels, the HST provided important constraints on models of the stellar "catastrophes" that produce these extraordinarily intense and rapid outbursts of energy.

• THE BIRTH OF STARS

The HST's resolution and sensitivity to both visible and infrared light have given it unprecedented, clear views of the rich, diverse and complex processes that lead to star formation. The collision of two galaxies is clearly seen by the HST to stimulate the birth of large populations of young, massive stars and star clusters. Compression of interstellar gas by the intense radiation from a massive star can trigger the formation of smaller stars nearby. The radiation and ejected material from supernova explosions are seen to enrich and compress the interstellar gas and dust from which new stars can form. Stars forming in large, dense clouds of molecular hydrogen and dust are limited in the masses they can achieve by the erosion of material away from those clouds by radiation from nearby hot stars. The formation of an individual star seems always to be governed by an accretion disk of material falling onto the protostar and highly aligned bipolar jets carrying material away from the "construction site".

• THE FORMATION OF PLANETARY SYSTEMS

Prior to the HST the presence of dust disks around a small number of young stars had been inferred from observations by infrared satellites and one such disk, around β Pictoris, had been directly imaged with a ground-based coronagraphic instrument. For centuries it has been believed that such a disk must have been the precursor to our own solar system, providing the raw material from which the planets were constructed. The existence of protoplanetary disks around other stars is, therefore, a necessary condition for the existence of extra-solar planetary systems. The HST has revolutionized this area of science. WFPC2 images of the Orion nebula region revealed a large proportion of young stars (about 50%) are surrounded by gas and dust structures, many of which are clearly disks. High resolution near-infrared images of the Taurus dark cloud and other star-forming regions taken with NICMOS show protoplanetary disks in the process of formation and evolution. These disks are common and they contain enough material to form entire planetary systems equivalent to our solar system. HST coronagraphic observations with NICMOS and STIS reveal, for the first time, the internal structures of protoplanetary disks and of the debris left behind by prior planet formation. Thus, the HST has opened a new area of observational astronomy, the empirical study of the structure and evolution of proto-planetary systems.

• **THE DEATH OF STARS**

Dying stars shed material into interstellar space, sometimes gently and episodically, sometimes in explosive catastrophes. In either case the ejected material is enriched in chemical elements produced in the interior nuclear furnaces of these stars and thus "seeds" the interstellar gas and dust with the basic building blocks from which new stars, planets and life may originate. The HST has provided exquisite images of dying stars. These are the basis for a remarkably detailed understanding of the events preceding the deaths of stars, how material is shed from dying stars, how that material interacts with the environment around the star, and how the process is influenced by each star's individual circumstances. Was the star single or part of a multiple star system, did it have planets, did it have a magnetic field, was it rapidly rotating, etc.? Perhaps the most spectacular example is the HSTs imagery and spectroscopy of supernova SN1987a. For the first time astronomers saw the delicate ring structures left over from the pre-explosion evolution of the dying star. They saw the blast debris expanding outward over time from the supernova explosion. Now they are seeing the innermost ring "light up" as the blast material plows into it.

• **OUR DYNAMIC SOLAR SYSTEM**

The HST provided the first resolved images of Pluto and its satellite Charon, enabling measurement of their masses and crude mapping of their surfaces. HST imagery has shown that the atmospheres of the gas giant outer planets Uranus and Neptune, once thought to be bland and nearly featureless, in fact possess very dynamic climates. Giant cloud patterns form and dissipate with regularity. The ultraviolet imaging capability of STIS and WFPC2 have given planetary scientists remarkable views of the northern and southern lights on Jupiter, Saturn and Ganymede. With the HST scientists have traced the dynamic electrical interactions between Jupiter and its satellite Io. In 1995 astronomers had the rare opportunity to view Saturn's rings edge-on. The HST's sharp resolution led to the discovery of a diffuse atmosphere surrounding the rings, discovery of several new satellites, and recovery of old satellites in strange positions. The implication is that we are watching satellites of Saturn being created and destroyed nearly in "real time". The HST has monitored the weather on Mars and has provided remarkable images of seasonal changes at the Martian poles. In 1994 the HST obtained uniquely clear pictures of the collisions of the 21 fragments of Comet Shoemaker-Levy/9 with the upper atmosphere of Jupiter and their aftermath. These revealed the enormous fireballs created when fragments entered the Jovian atmosphere at 140,000 miles per hour and heated the atmospheric gases up to 50,000 degrees F, cooking them into a stew of "soot" and organic molecules. Studies of atmospheric waves propagating away from the impact sites gave unique new information about the composition and density of Jupiter's atmosphere. The dispersal of the "soot" over several weeks allowed scientists to monitor the upper atmospheric winds. But the greatest contribution of the observing campaigns on Comet S-L/9 by the HST and by many other telescopes on earth was to remind humanity of our vulnerability as a planet and to motivate us to remain vigilant to the space environment in which we exist.

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