6. Panchromatic Science

The information on astrophysical sources contained in each of the UV, visible, and near-IR bands is strongly complementary to the other bands, since each band is affected differently by hot stars, cool stars, and dust. Emission and absorption lines suitable to probe in detail the physical properties of stars and the interstellar medium are found throughout this broad wavelength interval. Moreover, the redshifts of distant galaxies move important spectral features, located at short wavelength in their rest frame, into the observer's infrared band. At least one of the two most important features in the continuum of composite stellar populations – the Lyman break and the 4000 Å break – will be found within the wavelength range of WFC3 for redshifts throughout the range 0 through 12: an enormous volume of the Universe. For these reasons, many scientific programs would greatly benefit from a wavelength coverage from the UV to the near IR, the interval for which WFC3 is being designed.

There is another factor that makes the panchromatic WFC3 compelling. The two extremes of the WFC3 sensitivity interval correspond to minima in the zodiacal sky background generated by optical scattering of sunlight and IR emission by the dust particles in the plane of our solar system. The peak in zodiacal background occurs in the 5000-7000 Å region. On either side of this, however, there are very dark minima lying at 2000 Å in the mid-UV and at 3 μm in the near-IR. The HST OTA thermal emission shifts the minimum background wavelength in the infrared to 1.6 μm. In these deep windows the background is 40-100 times fainter than at any wavelength at the finest ground-based sites. It is also over 10 times fainter than the sky from HST orbit at wavelengths of 5000-7000 Å. With its panchromatic coverage, WFC3 is well suited to take advantage of both the UV and IR dark windows in observations of low-surface-brightness extragalactic objects. Applications include the study of faint circum-galactic regions in nearby galaxies (e.g. tidal streams), intergalactic clouds, dwarf galaxies, and galaxies and proto-galaxies at high redshifts (for which the surface brightness scales inversely as the fourth power of the redshift). Objects that have surface brightness up to 1000 times fainter than can be detected with ground-based telescopes will be identifiable with WFC3.

In the following subsections we discuss the contributions that the panchromatic capabilities of WFC3 will allow in three broad areas of astrophysical research.

6.1 Galactic Evolution

The most powerful insights into galaxy evolution will emerge from a *panchromatic* approach which combines the special features of the UV, optical, and IR spectral domains. Together, these offer the best probes of normal stellar populations and medium-temperature interstellar gas. These are the primary domains for galaxy astrophysics, without which the insights offered by other spectral bands (such as radio, far-infrared and X-ray) on very cold or very hot material are incomplete.

The power of panchromatic imaging to "dissect" the structure of galaxies is illustrated in Figure 10, which compares a 2500 Å image of the nearby spiral galaxy M81 to a normal R-band (6500 Å) image. Early-type spirals like M81 and barred galaxies tend to exhibit the largest morphological changes with wavelength. In the left panel of Figure 10 the UV morphology of M81 would be classified with a Hubble galaxy type dramatically different from that derived from its visible band morphology. The optical bulge is dominated by cool main-sequence and giant-branch stars, and it dims progressively at shorter wavelengths. By contrast, hot OB stars in the spiral arms increase in brightness in the UV so that the arms stand out. The UV images permit analysis of star-formation physics through detailed comparisons of massive star formation over the past few 100 Myr to the distribution of hot and cold interstellar gas (e.g., as measured by H□ emission and radio-band neutral hydrogen maps).

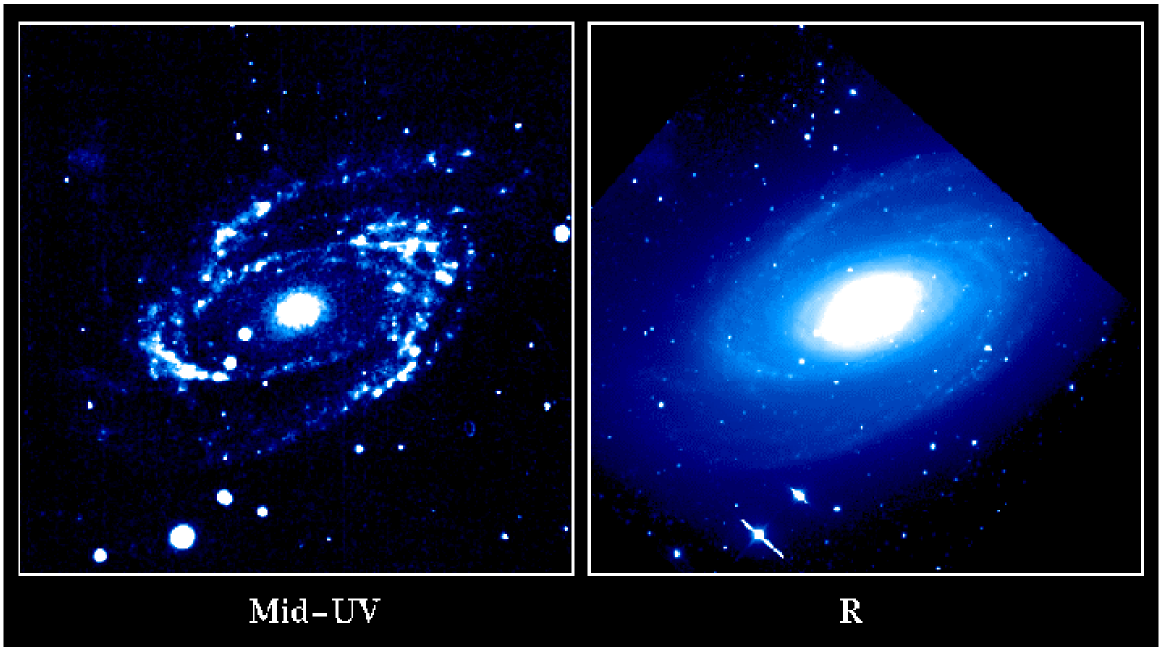

Figure 10. Images of the nearby spiral galaxy M81 at 2500 Å (from the Astro/UIT, left panel) and in the R band (6500 Å) right panel. The central bulge is dominated by cool main sequence and giant branch stars, and it progressively diminishes at shorter wavelengths. By contrast, hot OB associations in the spiral arms increase in brightness in the UV so that the arms stand out (R.W. O'Connell.)

In contrast to the UV, the near IR H band (1.6 μm) flux is mostly sensitive to stellar mass, with little dependency on age and metallicity (see Figure 11.) Multiband imaging from the UV to the near IR allows one to correct for the omnipresent effect of dust obscuration, e.g., by using the so-called dust-insensitive color combinations. Panchromatic UV-to-IR imaging of nearby normal galaxies also serves as a basis for interpreting galaxies at high redshift. The rest-frame UV continuum is measurable to very high redshifts (z □ 10) with instruments like NGST and serves as a key index of the cosmic star-formation density as a function of time. Panchromatic images of nearby galaxies are also necessary to calibrate the large "morphological K-correction" which arises because of the strong changes in galaxy appearance with rest wavelength. This must be quantified in order to distinguish genuine evolutionary effects from simple band-shifting. For example, M81 (Figure 10) has an almost ring-like appearance in the UV. A high-redshift version of M81 observed in the restframe UV might be mistakenly interpreted as a short-lived, non-equilibrium system rather than the stable structure we know it to be.

With multiband WFC3 exposures, astronomers will make important strides in understanding the astrophysical drivers of galaxy UV luminosities, the cosmic star-formation history over the past few Gyrs, and the nature of the strange systems detected at high redshifts.

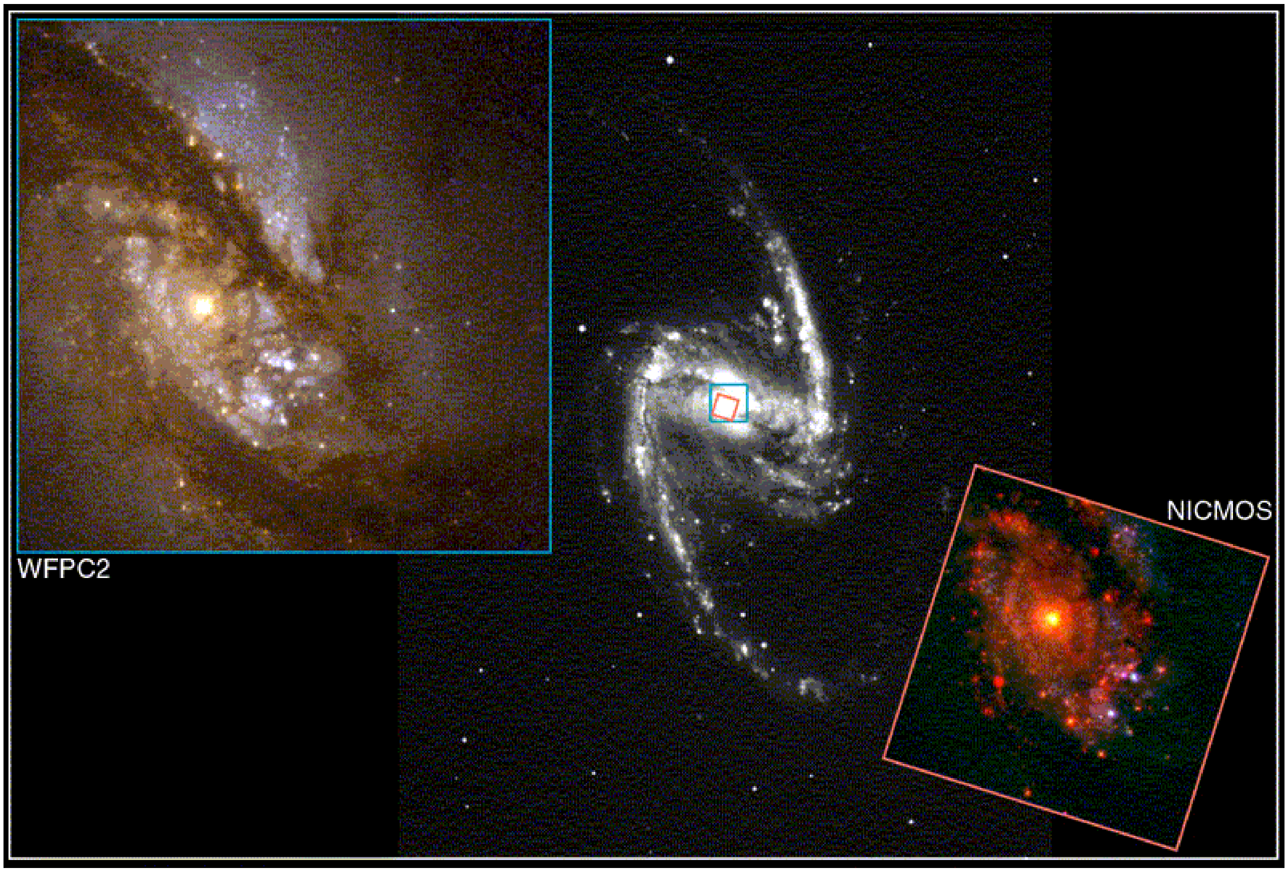

Figure 11. The nucleus of the active, star-forming galaxy NGC 1365 imaged with WFPC2 (upper left inset) and NICMOS (lower right inset) and from the ground (central image). Some of the star clusters visible in red in the NICMOS image are enshrouded in dust and undetectable in the WFPC2 images. The infrared image traces the intrinsic stellar mass distribution better than the visible light image. The bright source at the center is the active nucleus (M. Carollo and NASA).

6.2 Star Birth, Death, and the Interstellar Medium

Images of gaseous nebulae obtained by HST's WFPC2 are as astounding to experienced astronomers as they are to the general public. WFPC2 exposed the processes by which stars form in the dense cores of cold, dusty, and dark molecular clouds, why stars form prodigiously in some galaxies but not in others, and how they end their lives by shedding their outer layers. WFC3 is a fitting legacy of WFPC2. The difficult questions posed by WFPC2 will be attacked in detail by WFC3, providing new images that will form the basis of research long past the decommissioning of HST in 2010. WFC3 extends the spectral coverage as well as the sensitivity of WFPC2, and adds a host of important new filters for new types of scientific investigations.

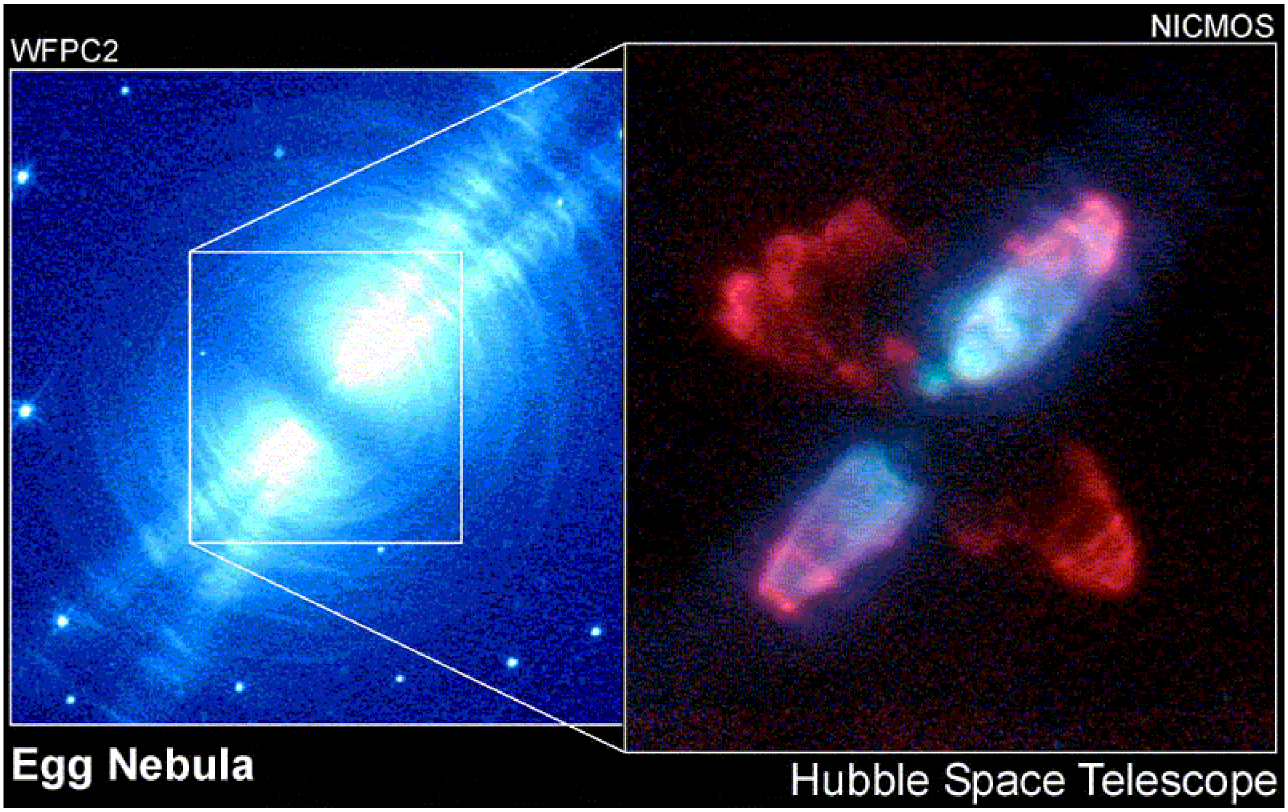

Figure 12. WFPC2 (left panel) and NICMOS (right panel) images of the Egg Nebula (R. Thompson, D. Hines, R. Sahai, and NASA). The NICMOS image is color coded. The red features correspond to emission from hot ionized gas, the blue features to starlight reflected by dust.

(a) Stellar Outflows

WFC3 will be used to measure the physical, chemical, and ionization structures in the powerful winds emitted by both young and old stars, such as T Tauri stars, luminous blue variables, Herbig-Haro objects, Wolf-Rayet bubbles, planetary nebulae (see Figures 12 and 14), and novae.

Infrared images are necessary to probe heavily reddened objects with strong scattering. These studies will allow us to connect the births of stars to their surroundings, and to see how dying stars stir up and enrich the inter-stellar medium with their winds. Direct imaging in the 1.64 μm [Fe II] line with WFC3 will allow observers to probe winds in young stars down to the scale of our solar system, which should constrain possible formation mechanisms.

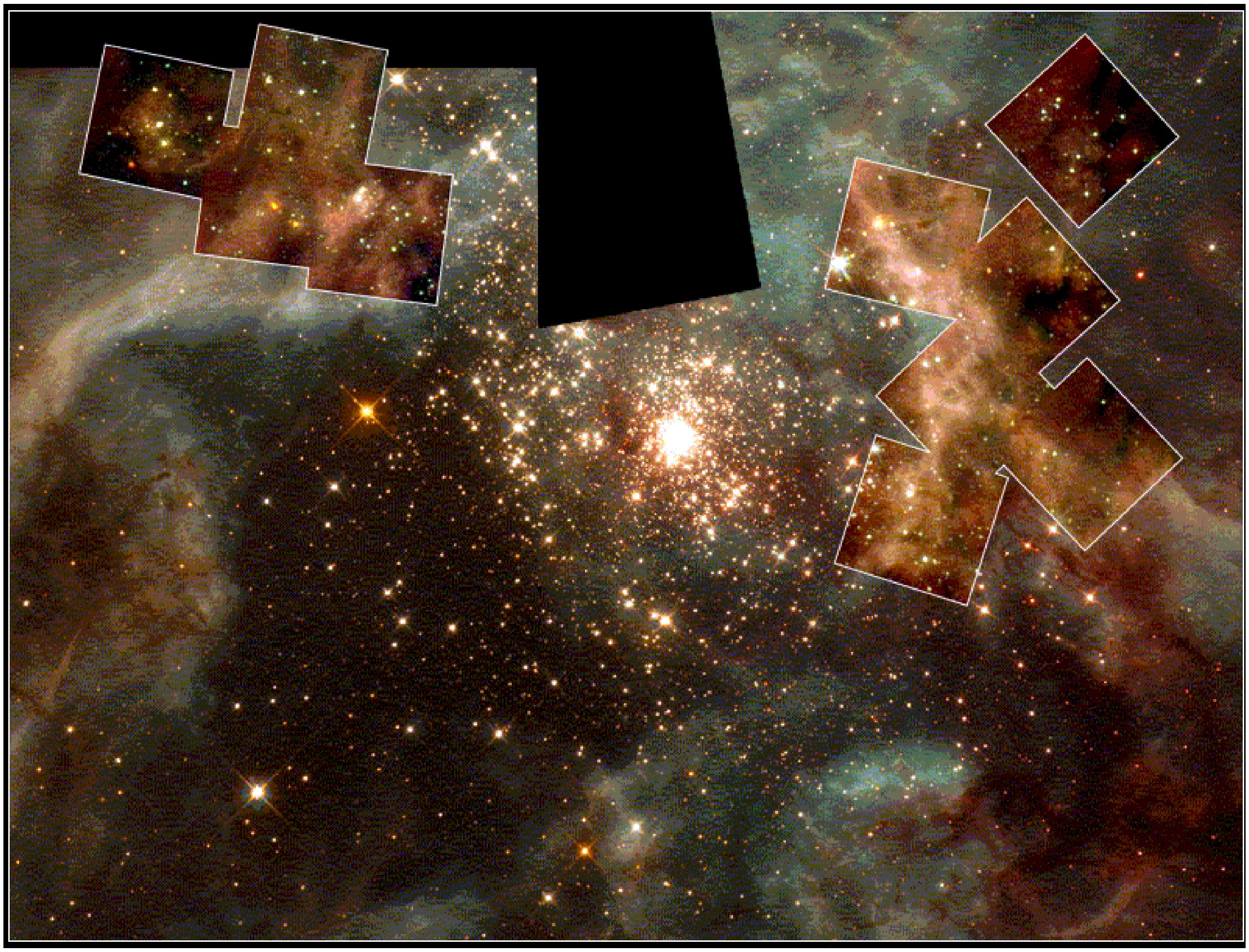

Figure 13. Composite WFPC2 (background image) and NICMOS Camera 2 mosaics (smaller insets) of the 30 Doradus Nebula in the Large Magellanic Cloud (N.Walborn, R. Barba and NASA.) The NICMOS images allow us to study the dust-enshrouded star-formation triggered by the bright star cluster visible in the WFPC2 image. The IR channel of WFC3 would allow us to cover the whole area shown with just two exposures instead of the 10 used to get partial coverage with NICMOS Camera 2.

(b) Initial Mass Function

Near-infrared imaging with the HST offers unparalleled opportunities to cut through surrounding dust cocoons (see Figure 13) to measure the initial mass function to below the hydrogen-burning limit in different galactic environments. WFC3's sensitivity to the infrared water vapor and methane features that are characteristic of the lowest-mass stellar and sub-stellar objects provides a powerful capability for studying low-mass stars and brown dwarfs. The important water feature is unobservable from ground-based facilities because of the strong absorption by the Earth's atmosphere. These studies may help us to understand the origin of the similarities and differences in the initial stellar mass function throughout the Milky Way and nearby galaxies.

(c) Formation of Planetary Nebulae

Using WFC3, astronomers will obtain critical data on the mass ejection that ordinary stars like our Sun undergo as their lives end. These stars eject their outer layers in beautiful and intricate patterns (see Figures 12 and 14) that were never predicted by the otherwise highly successful models of stellar evolution. WFC3's panchromatic cameras will provide much improved temperature, composition, and density probes of such planetary nebulae. Motions of HST-resolved small emission knots caught up in the flow like tracer particles permit us to determine distances to these objects and their dynamics with much better accuracy.

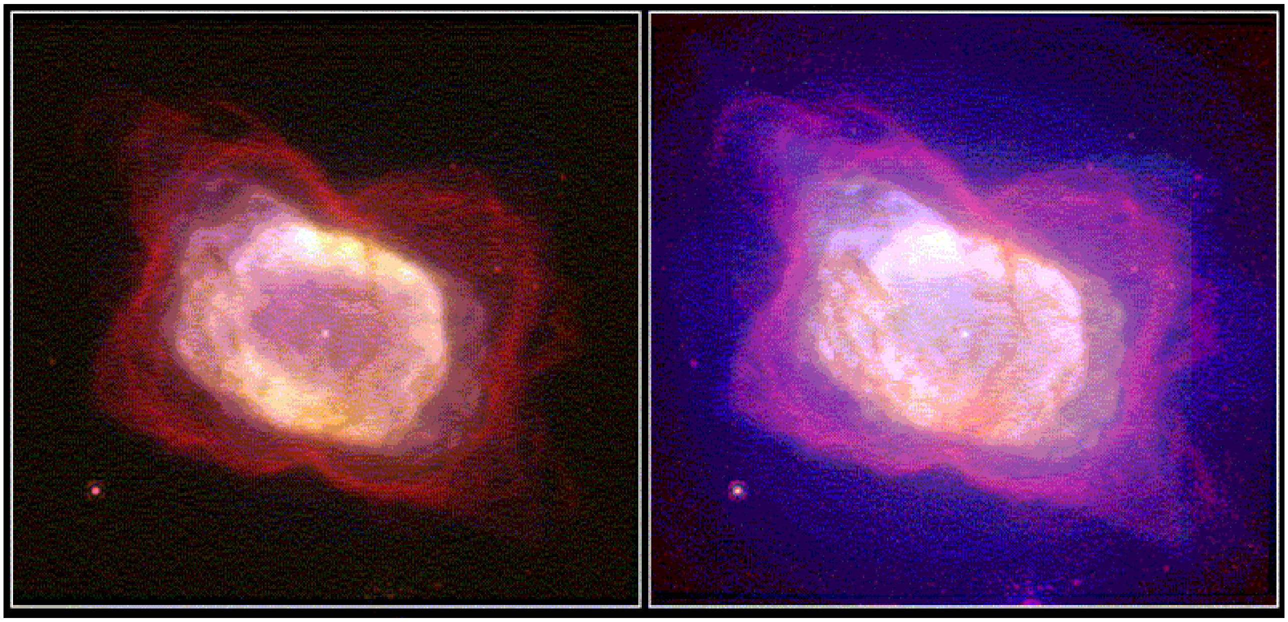

Figure 14. The planetary nebula NGC 7027 imaged with NICMOS (left panel) and NICMOS plus WFPC2 (right panel). In the left panel the red color represents cool molecular hydrogen, the white area represents gas ionized by the central star. In the right panel, in addition to the ionized gas (white) and the molecular gas (pink and red), the area where the star light is reflected off dust is visible in blue (W. Latter and NASA).

(d) Physical Structure of Galactic Nebulae

WFC3 will be used to investigate the small-scale ionization structure of Galactic nebulae (Figure 15.) The physics of these objects is largely determined by hydro-dynamical and radiative-transfer effects with characteristic scalelengths of order $10^{15} – 10^{16}$ cm which, for nearby nebulae, correspond to typical angular scales of 0.1 to 1 arcsec. Examples include the structure of ionization and shock fronts in H II regions, supernova remnants, and stellar outflows. Understanding the physics of these structures underlies interpretation of a wide range of astrophysical phenomena. The improved quantum efficiency and sampling of the WFC3 CCDs relative to the WFPC2, together with the availability of a more comprehensive wide-field narrow-band capability than offered by ACS, will make the WFC3 the premier instrument on HST for this work.

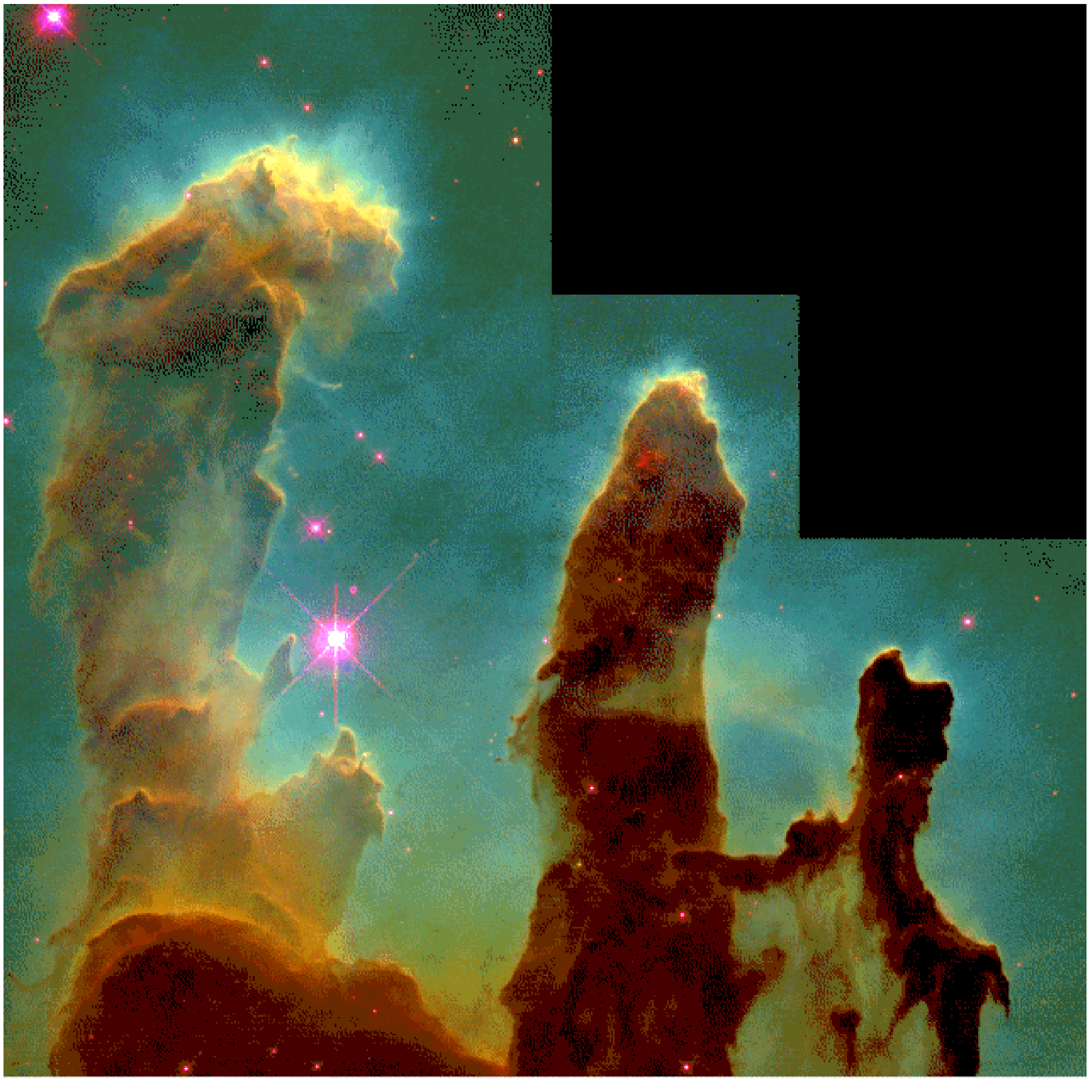

Figure 15. WFPC2 image of the galactic nebula M16. The image shows low-ionization sulfur emission ([S II]) as red, hydrogen recombination emission as green, and high-ionization oxygen ([O III]) emission as blue. The image emphasizes the small-scale structure that dominates much of the physics of the interstellar medium (J. Hester and NASA.)

(e) Young Stellar Objects and their Surroundings

WFC3 will probe deeply into interstellar molecular clouds where stars are born and investigate the surroundings of young stars as they form and evolve. The infrared emission, both from atomic and molecular tracers and from dust-scattered starlight, can escape from the cloud and be detected, whereas visible light is essentially completely absorbed (Figure 16.) Certain zones at which winds from the collapsing star batter the gas around them can be uniquely mapped using the diagnostic lines of [Fe II] line at 1.64 μm.

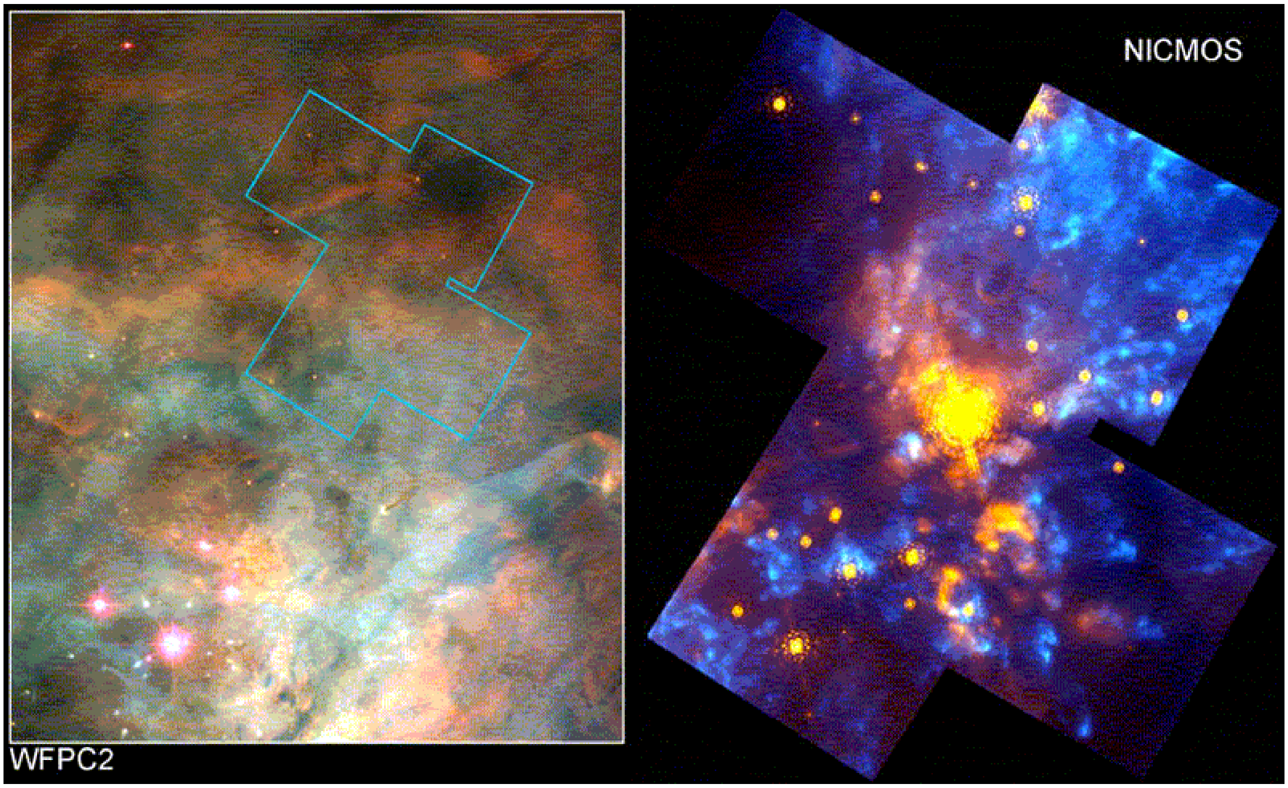

Figure 16. A region in the Orion molecular cloud OMC-1 imaged by WFPC2 (left panel) and NICMOS (right panel). In the NICMOS picture emission from excited molecular gas is in blue while stars and hot interstellar dust are yellow-orange.The brightest object in the NICMOS image is a hot massive star enshrouded in dust and completely invisible in the WFPC2 image (R. Thompson, S. Stolovy, C.R. O'Dell, and NASA).

(f) Starburst Galaxies and their Triggering Mechanisms

WFC3 will observe intense "starbursts" in other galaxies (Figure 17.) The triggering mechanisms of such unusual episodes are not understood. Furthermore, the link between starbursts and their host galaxies provides clues to the evolution of galaxies as a whole, and ultimately will clarify the connection between low- and high-redshift galaxies. WFC3's panchromatic design extends observations into the ultraviolet, where the most massive stars formed in a starburst are observable, as well as into the infrared, where the youngest stars still swaddled in dust can be unveiled. The combination of this information allows the mass distribution of the stars formed in the starburst to be inferred, and allows comparison to star formation in less energetic environments such as those found in the Milky Way.

Similarly, the impact of super-winds from active galactic nuclei is poorly understood. Studying the enormous energy released by these winds, as well as physical phenomena which drive them, will yield clues to their role in the evolution of galaxies from high to low redshifts. In particular, with its wide band coverage and selection of special emission-line filters, WFC3 is by far the best tool for such studies.

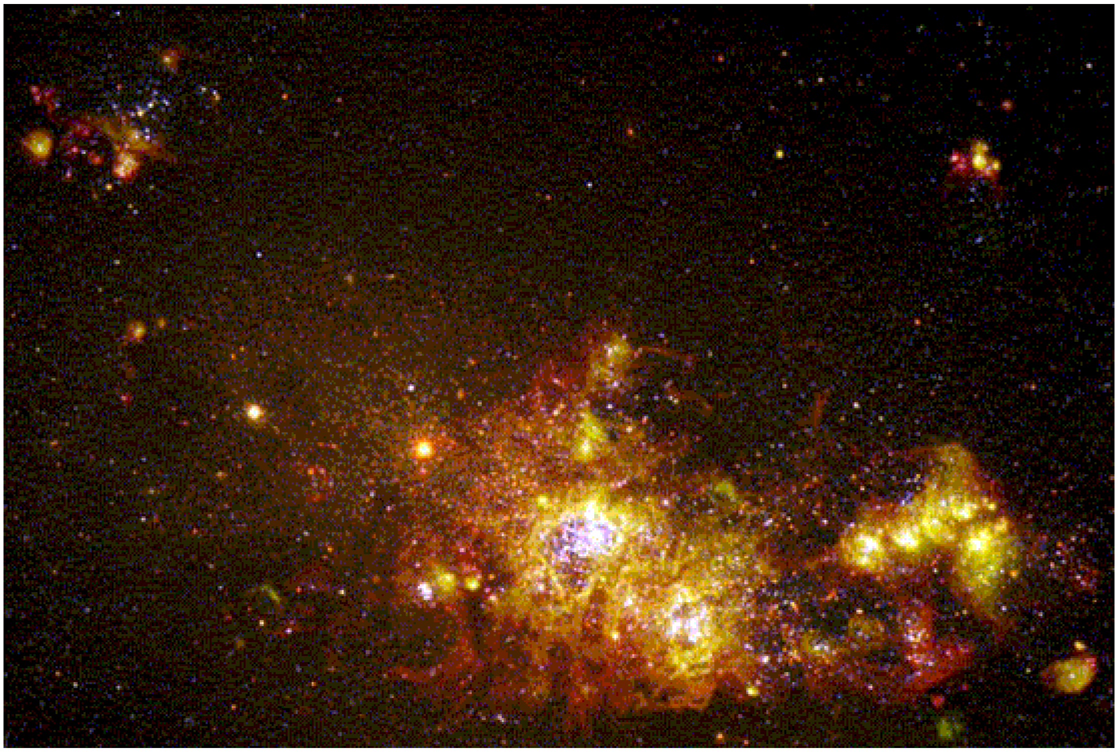

Figure 17. “True” color image of the starburst galaxy NGC 4214 (Hubble Heritage Team, J. W. MacKenty and NASA.) Visible are the older diffuse stellar population (in red), star formation regions (white), and gas filaments (in yellow.)

6.3 Meteorology of the Outer Planets

WFC3 will be a prime instrument for studying weather patterns and climatic variations on the outer planets. Given their very long orbital periods (12 years for Jupiter, 30 for Saturn), the evolution of the weather patterns requires monitoring over long timescales (Figure 18.) Moreover, high sensitivity is required since data have to be collected with high spatial resolution and with integration times short enough to avoid smearing due to the rotation of the planet (for all outer planets the day is less than 24 hours long). Studying the weather on other planets will improve our knowledge of terrestrial weather by allowing meteorologists to refine their models. WFC3 will dramatically improve the already excellent capability of HST in this field. A few examples are illustrated below.

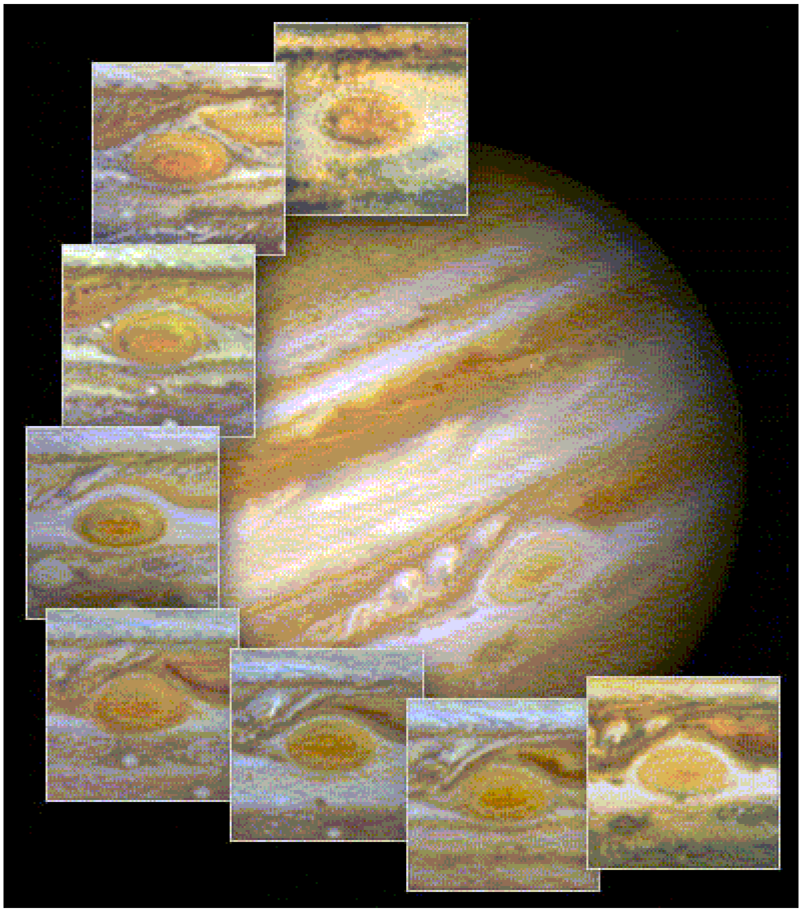

Figure 18. Jupiter's Great Red Spot evolution in the period 1992-1996 as revealed by WFPC2. (Hubble Heritage Team, A. Simon and NASA.) WFC3 will be able to carry out similar studies in the visible and in the near-IR, probing to different depths in the Jovian atmosphere.

Cloud activity in the atmosphere of Uranus is changing rapidly as the planet approaches its equinox (2007). In contrast to the bland and featureless planet seen during the *Voyager* spacecraft encounter in 1986 at the time of solstice, methane band images taken now with WFPC2 on HST show clouds forming and dissipating on timescales of several to tens of days. These short- and long-term changes appear to mark a major alteration in the thermal structure and circulation regimes on a seasonal timescale, now seen for the first time. Images of Uranus with the near-IR channel on WFC3 in a strong methane band (e.g., 1.38 μm), augmented by nearly simultaneous images in the weak (0.62 μm) and medium strength (0.89 μm) methane bands with the UVIS channel, will establish the nature of the changes in greater detail than previously available, since each methane band probes a different depth in the Uranian atmosphere.

The atmosphere of Neptune (see Figure 19) undergoes episodic outbursts, during which time the global brightness in the near-IR changes by nearly a factor of four. Observations in the methane band similar to those outlined for Uranus would be valuable in probing Neptune's atmosphere to understand the source of these outbursts.

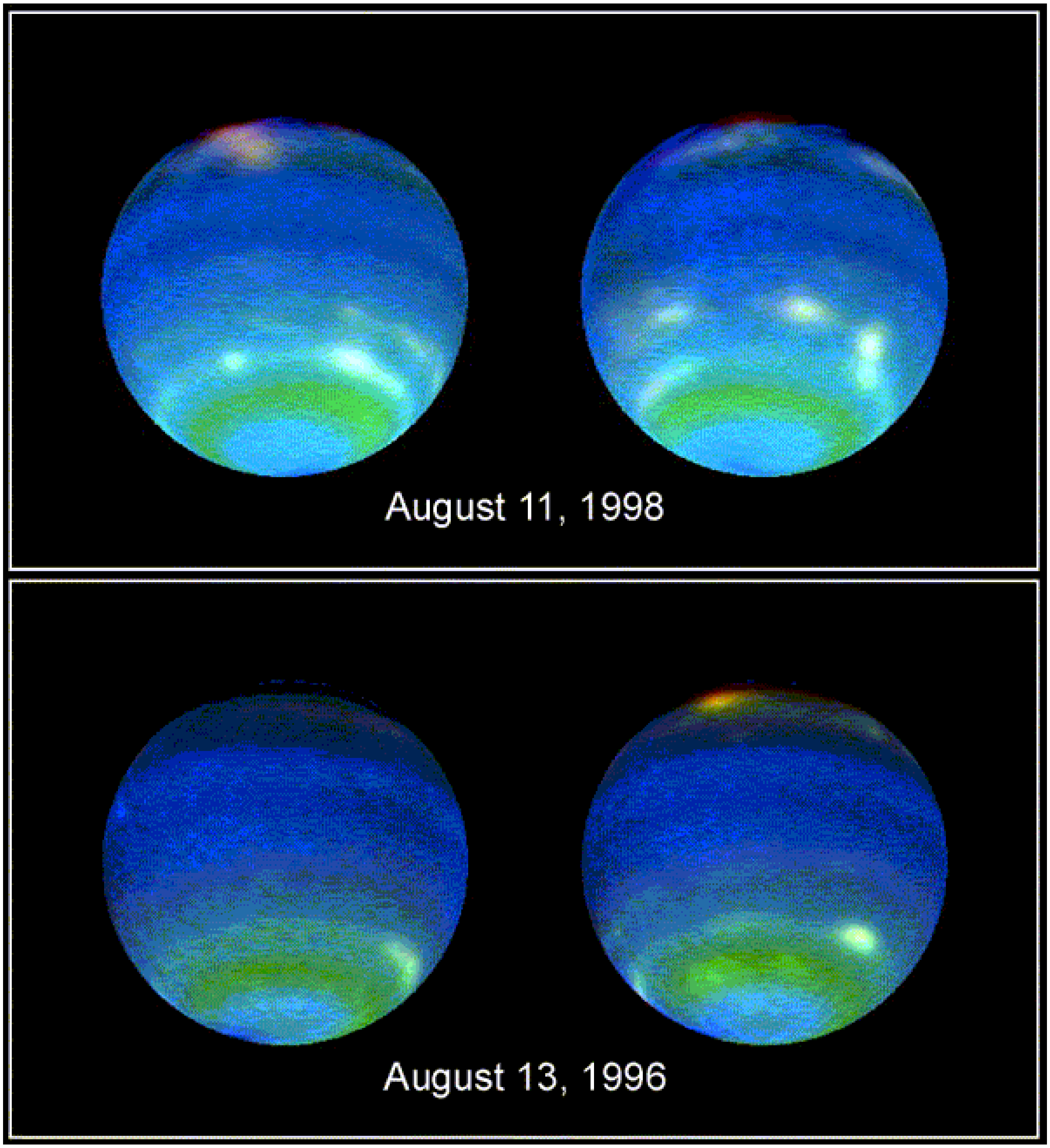

Figure 19. Dynamic weather patterns in Neptune as shown in WFPC2 images (L. Sromovsky and NASA). Each panel shows the short term evolution of cloud patterns on Neptune with 900 miles an hour winds and huge storms the size of the Earth coming and going with regularity.

The atmosphere of Titan is a prime target of the Cassini/Huygens mission currently en route to the Saturn system. The satellite's surface has been observed with HST at near-IR wavelengths where methane opacity is low and particulate scattering is minimal. Two years of more detailed and more sensitive images with WFC3-IR would provide the characteristics of Titan's variable atmospheric activity and some aspects of the surface, establishing the context for the

Cassini/Huygens encounters that will begin in 2004.