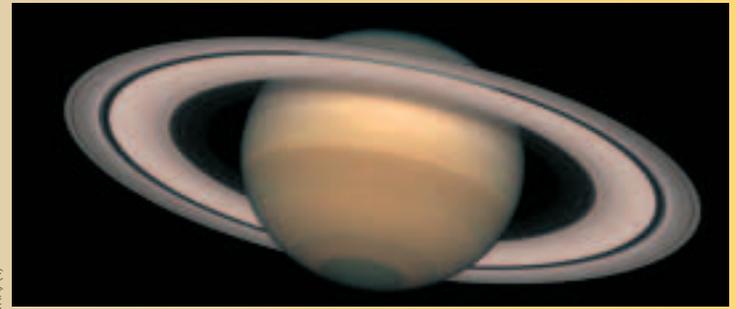
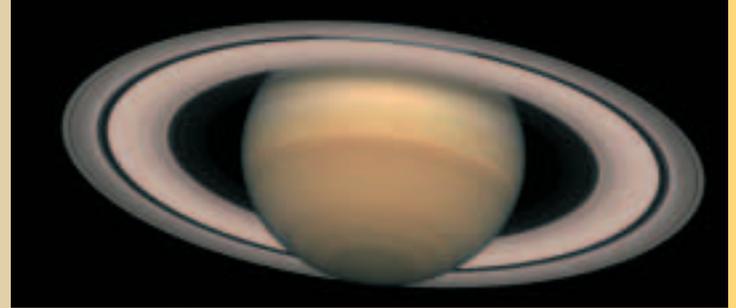




[1]



NASA AND THE HUBBLE HERITAGE TEAM (STSCI/AURA) (4)

[2]

Creating Hubble's

For nearly a decade spectacular color pictures from the Hubble Space Telescope (HST) have awed and inspired the world. Some Hubble pictures have become cultural icons. They grace not only the covers of newspapers, magazines, and nearly every astronomy textbook, but also music album covers, advertisements, T-shirts, coffee mugs, movie scenes, and even a Pepsi-Cola Company corporate report. Hubble's images have ushered in a golden age of popular interest in astronomy, bringing new views of the universe as culturally seminal and evocative as the Apollo images from the Moon were a generation ago.

The flat-out gorgeous Hubble spacescapes look too good to be true. Are these objects really so colorful? If we could fly out to these celestial wonders, would they look this way to our eyes? If not, as a few hard-core NASA cynics claim, are the pictures being overly colorized to seduce the public?

What is "truth" when it comes to Hubble's universe?

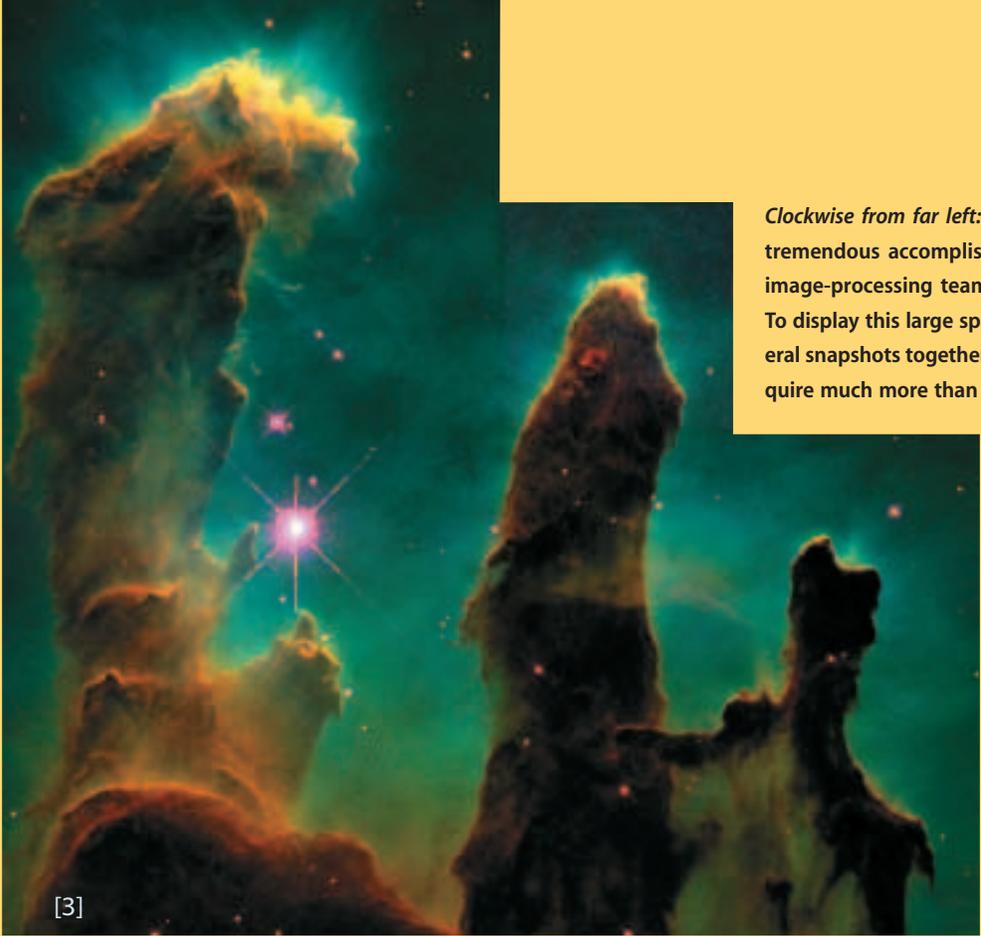
[4]



NASA / ACS TEAM



SkyandTelescope.com



Clockwise from far left: This gallery of celestial wonders demonstrates the tremendous accomplishments made daily by the Hubble Space Telescope image-processing team. The breathtaking views begin with NGC 4414 [1]. To display this large spiral galaxy, engineers had to painstakingly stitch several snapshots together to make the mosaic we see here. But the pictures require much more than just stitching. Since all of Hubble's raw images begin

as black-and-white shots, each view must be colored to enhance subtle features. In Saturn's case [2], engineers used ground-based images to color-correct the planet. Other images, such as the Eagle Nebula [3], contain features so subdued that the human eye could never see their true majesty. In these cases, image processors assign specific colors based upon given wavelengths of atomic emission. Finally, Hubble presents "the Mice" (NGC 4646 A and B). These interacting galaxies [4] were snared by the Advanced Camera for Surveys, Hubble's newest, most sharp-eyed instrument. With it, the telescope will see views of the heavens never before possible.

J. JEFF HESTER, PAUL SCOWEN, AND ARIZONA STATE UNIVERSITY

Technicolor Universe

Behind every gorgeous Hubble Space Telescope image,
there's much unsung work — and a lot of judgment calls.

BY RAY VILLARD AND ZOLTAN LEVAY

The Eye of the Beholder

Our guiding philosophy at the Space Telescope Science Institute (STScI) News Office, which has prepared hundreds of public Hubble pictures, is that creating an honest full-color image from astronomical data is as much an art as a science. When processed correctly, an attractive and evocative picture brings out the scientific content within. We strive to prepare Hubble images for the public that tell a *science* story. The techniques we use to enhance color, emphasize contrast, or show specific details are almost always selected with “the story” in mind.

Some of the most popular Hubble images result from observations that were made for a very specific scientific purpose. Such pictures are fortuitous byproducts, yet they often enhance the science. An aesthetic scene that has proper tonal balance and color variation will yield new information and insights. Our eyes are better at distinguishing differing hues than differing gray values, so edges and otherwise hard-to-see features often pop out in a color image.

Telescopes are, by design, built to enable us to see faint objects we could never hope to observe with our naked eyes. The light and color from nebulae, for instance, are usually very feeble. So, even when we look through a telescope, the color-sensitive cone cells in our retina mostly give up. The rod cells — our dim-light receptors — do most, if not all, of the work, and they see only in black and white. Nebulae therefore look grayish in the telescope eyepiece, with only the slightest hint of color. The same would hold through a spaceship’s porthole. Thus the question of *true color* becomes largely moot since we can’t perceive it in the first place.

Like beauty, color is in the eye of the beholder. The human

eye-brain “computer” has its own unique way of collecting and decoding the signals from our cones. Photographic film and the CCDs (charge-coupled devices) in camcorders and digital cameras mimic the retina’s red, green, and blue cones by recording the three colors separately. The components are later reassembled into a full-color image. But these devices are not *completely* faithful to how the eye handles color information. For example, camcorders tend to make cyan look extra blue. Many color films have better response to red light than the eye. Some films deliberately boost color saturation (vividness) for a “livelier” picture. Paul Simon sang of this in his 1973 hit “Kodachrome” when he described the classic Eastman Kodak transparency film as misleading: “Makes you think all the world’s a sunny day, oh yeah!”

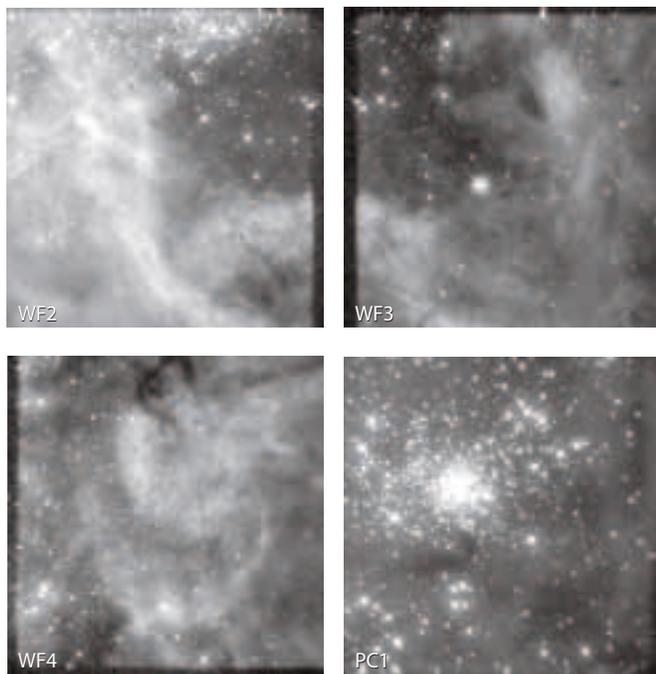
There’s even more room for confusion in other image-display media. The dyes in photographic prints, much less the inks in magazines, cannot duplicate the saturated colors offered by computer-screen phosphors. Nor do they come near the broad dynamic range, from bright to dark, that computer screens offer.

Out-of-This-World Color

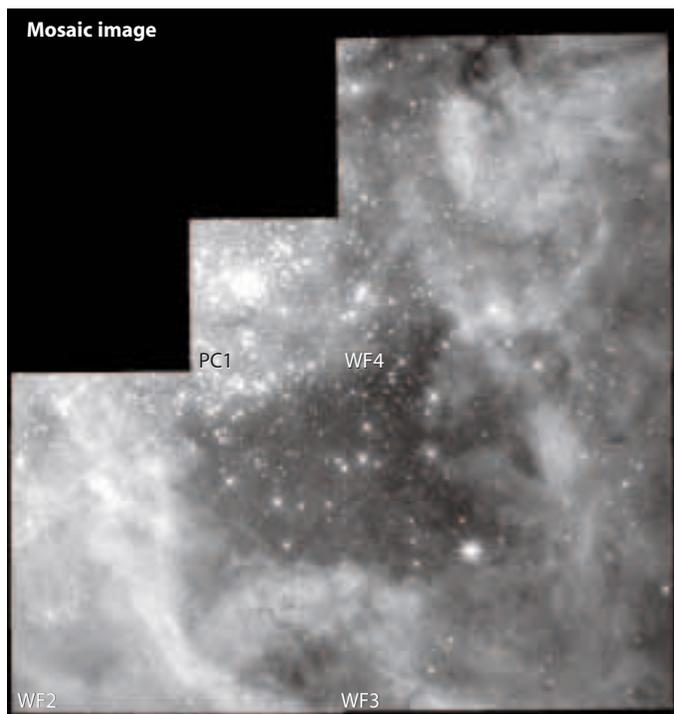
Our news office always strives for “natural” color in preparing Hubble images. This involves a careful selection of hues that accurately reflect the color filters through which the original images were taken. Every Hubble exposure is, in fact, black and white. Color images can be assembled from these monochrome exposures because they are usually taken through different color filters. The choice of filter is a judgment call that may be easy or difficult depending on how a given target emits or reflects light.

How we perceive an object’s “true” astronomical color depends on its nature, specifically on whether (and how) it

Individual WFPC2 chips



Mosaic image



The layout of CCDs in Hubble’s Wide Field and Planetary Camera 2 (WFPC2) is responsible for the “stealth bomber” shape of many famous Hubble pictures, such as the Large Magellanic Cloud’s 30 Doradus here. Three wide-field chips each cover a square 70 arcseconds on a side; the smaller, higher-resolution planetary-camera chip (PC1) in the center is only 35 arcseconds wide.

emits or reflects light. Planets absorb certain wavelengths of starlight and reflect the rest. For example, the cyan hues of Neptune and Uranus are due to methane in their atmospheres absorbing red light. Mar's ruddy hue is due to iron oxides that absorb green wavelengths.

In nebulae, emission of light at certain wavelengths produces specific colors. Nebulae glowing with fluorescent clouds of hydrogen, oxygen, and nitrogen are nature's own version of a honky-tonk strip of neon lights. Because thin gases glow only at specific wavelengths, these colors are pure, distinct, and very saturated. Conversely, star colors are quite unsaturated and pastel because they represent a classic blackbody spectrum. Yes, they may peak in red wavelengths like Betelgeuse or blue wavelengths like Spica, but they emit so much light at every other color that their resulting hue is subdued because it stimulates all the cones in our eyes simultaneously.

Hubble's Rainbow Vision

Hubble's longtime workhorse instrument is the Wide Field and Planetary Camera 2 (WFPC2), installed in 1993. Its three wide-field CCDs combine with a fourth chip that has twice the resolution but one-quarter the field of view to create the trademark stairstep image shape. Here at STScI we not-so-affectionately call it the "bat plane" or "stealth bomber," and it has been the bane of photo illustrators everywhere.

The newest kid in HST's instrument bay is the Advanced Camera for Surveys (ACS) — astronomy's new super-camera (March issue, page 34). Its first images burst onto the front pages of newspapers worldwide a few weeks after the March 2002 Hubble servicing mission with truly awesome new views of the dynamic and effervescent distant universe (July issue, page 28; August issue, page 48). With more than twice the imaging area of WFPC2, three times the sensitivity, and slightly higher resolution as well, it can be considered 10 times as efficient per frame. The ACS combines two large CCDs to yield a modem-choking 16 megabytes per snapshot — as opposed to 2.4 megabytes for WFPC2! It promises to provide huge and razor-sharp images of the cosmos so detailed that normal-size print magazines really can't do them justice. Their full glory will ultimately require large photographic prints, and they will be suitable for display on IMAX movie screens.

From Photons to Photos

All HST exposures ever taken — several hundred thousand so far — are stored on optical drives at STScI and are easily accessible by anyone with an HST archive account. The archives store raw data, the exact readouts from the cameras. However, when requested from the archive, the images are automatically calibrated on the fly with the most up-to-date corrections. Various pixels on the CCD detectors respond to light differently, and calibration corrects for the lack of conformity. Such imperfections occur on all CCD chips, whether professional or

All Hubble's CCDs withstand random cosmic-rays hits that appear as white spots and streaks. To remove this "noise," astronomers use a clever trick. They take at least two identical images of the same field and compare them. Any mark that appears in one image and not in the other is removed. Since cosmic rays are unlikely to hit the same pixel twice, the combined image is clear of blemishes.

commercial grade. The file is then sent out to astronomers in a common astronomy data format called FITS (Flexible Image Transport System).

From there, the next step is to remove the cosmic rays that strike the CCD detectors and leave hot pixels and wormlike trails. Like snowflakes accumulating on a sidewalk, the longer the exposure the more cosmic-ray hits accumulate on the CCDs. Due to this problem, most Hubble pictures are minimally two exposures of the same scene, layered atop one another. Because the cosmic-ray-hit pattern is unique to each exposure, cleanup software simply searches the matched shots and removes anything that appears in only one.

At this stage the pictures are manipulated in an astronomical image processing system called IRAF (Image Reduction and Analysis Facility, developed at the National Optical Astronomy Observatory with further enhancements by STScI). IRAF provides a suite of powerful tools for analyzing large astronomical images and extracting important information from them such as magnitudes and spectral signatures. Another commonly used software package is IDL (Interactive Data Language), a commercial product from the Eastman Kodak subsidiary Research Systems, Inc. But the Hubble color composites are usually done in the widely used commercial program *Adobe Photoshop* because of its flexibility and powerful user interface.

Individual images with cosmic rays

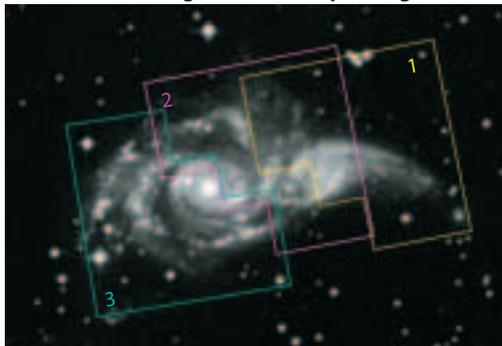


Combined and cleaned image



ZOLTAN LEVAY (STScI)

Ground-based image with WFPC2 pointings

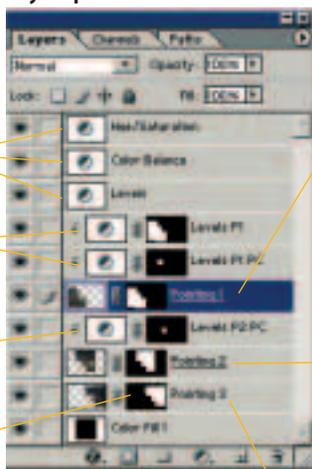


Resulting composite panorama



ZOLTAN LEVAY (STSC)

Layers palette



Global adjustment layers

Levels adjustments for pointing 1 (grouped with image layer)

Levels adjustments for pointing 2 planetary camera chip only

Layer mask

WFPC2 pointings



Pointing 1



Pointing 2



Pointing 3

The widest-field Hubble views are stitched together from multiple images using *Adobe Photoshop*. Engineers assembling the pieces adjust the brightness levels and compare the work in progress to ground-based observations. See page 36 for the completed product.

Compressing Dynamic Range

Studio photographers are taught to set up lighting so that the range of brightness between highlights and shadows is never more than 3:1. But a scene of brilliant stars, inky-black sky, and soft, subtle nebulae can have a dynamic range of a million to one! To be displayed with paper and ink, where the contrast ratio is, at best, 20:1, an exposure's bright, midrange, and dark elements must undergo meticulous image processing.

Most of these adjustments are done by eye, as anyone who has ever done darkroom photo printing will appreciate. *Adobe Photoshop* displays a histogram that helps us in assessing what needs to be done. The histogram is a graph showing the number of pixels at each brightness value (April issue, page 114). Star-field histograms are skewed toward the "0" bin because most of the field is black. A rich nebula is more like a standard daytime snapshot; its distribution is much like a bell curve, meaning that most of the pixel values are in the midrange and drop off toward the highlights and shadows.

As a first step, the image processor selects a "clip" level to chop off all pixels above a certain brightness level and display

them all as pure white. These represent overexposed stars. Clipping the whites gives room to stretch the midrange values so they show a proper tonal range — fundamental for any quality photo. Another approach is to convert the range of brightness values from a linear to a logarithmic scale. This compresses the bright values and stretches the midrange.

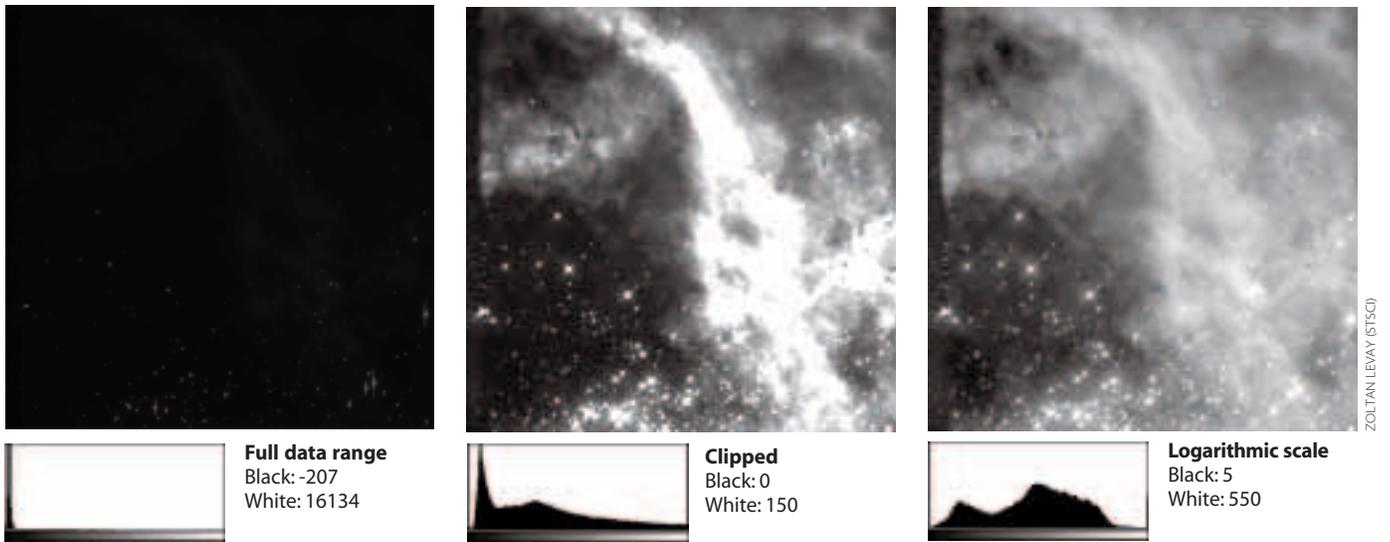
Once the contrast is optimized, the result is an "aesthetic" picture — one with a smooth distribution of gray tones strung between black and white. Of course, before a color image can be put together, each one of the monochrome exposures must undergo similar processing.

Composite Color

The imaging specialist assembles a color composite by carefully overlaying at least two, ideally three black-and-white images taken through different color filters. In a typical HST composite-color picture, one 8-bit monochrome image is used for each of the three color channels: red, green, and blue. This yields a 24-bit color image, one containing potentially 16.7 million (2^{24}) color values — enough to display all color gradations smoothly and realistically.

Photographic film divides the visible spectrum into three broad wavelength ranges that mimic those of our red, green, and blue cones. But HST's visible-light and infrared cameras have a vast collection of filters. Some are the broadband type that work much like photographic film layers. Many others transmit only a narrow range of wavelengths. On WFPC2 the filters are fine-tuned to the colors of various ionized gases found in nebulae: blue-green doubly ionized oxygen (O III), red neutral hydrogen (H α), red singly ionized nitrogen (N II), and blue singly ionized helium (He II). The ACS also has narrowband filters for oxygen, nitrogen, and other elements' emission lines, but not as many as WFPC2. Additionally, the ACS filters are custom made for looking at redshifted galaxies.

Unlike balancing a studio portrait to show flesh tones realistically, it is much trickier achieving a color-balance representative of the largely unseeable. There are very few standards against which to compare HST images. Planets are the easiest to color-balance because we can actually see them through amateur telescopes, and we understand their reflectance spectra. Even balancing galaxy images is fairly straightforward because the star colors follow blackbody spectra from hot pale blue to cool orange-red. We instinctively know the proper color for pale blue OB stars, pale orange-red giants, and the milky beige glow of the main-sequence population. But nebulae



ZOLTAN LEVAY (STSC)

This view of the 30 Doradus complex shows the importance of brightness scaling. The first panel is the raw image from the telescope. The pixel range stretched from the blackest space to well past the bright saturation limit of the detector. To fix the problem engineers first clipped off the extremes to bring out the “important” pixels. They then changed the linear scale to a logarithmic one. This compresses the range of brighter pixels and stretches the midrange. The result is a smooth distribution of black and gray tones — a visually pleasing presentation.

lae are problematic, because they glow only at specific, narrow wavelengths that may fall in gaps between the chosen filters. And even if they do match the filters, the resulting colors may not yield a full and rich spectrum to display.

Real and “Representative” Color

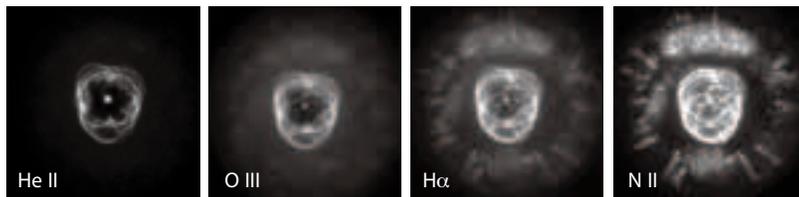
The closest HST approximation to a “true color” image is actually assembled from broadband-filter exposures, which nicely slice the visible spectrum into three equal parts. The slices closely match our eyes’ red, green, and blue response. Broadband filters encompass emission from multiple spectral lines, and this lessens the inherent color contrast in a nebula. The resulting colors are relatively unsaturated and pastel.

Some of Hubble’s most popular pictures, like those of the iconic Eagle Nebula (M16), are more problematic when it

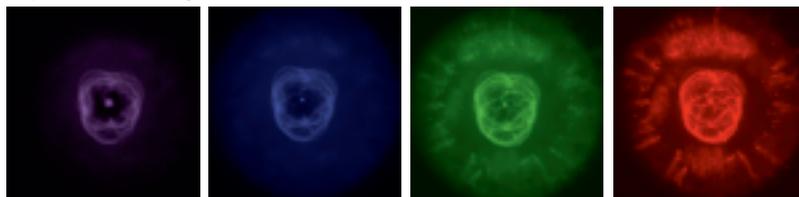
comes to the meaning of “true color.” The Eagle Nebula was imaged with filters for O III, H α , and singly ionized sulfur (S II). But because the red hydrogen emission band is a slightly shorter wavelength than the (also red) sulfur band, hydrogen was displayed as green. This provided for a full spectrum of colors. The term most commonly used for this approach is “representative color” — the eye’s three primary colors are assigned to narrowband filters according to the filters’ relative placement in the spectrum.

A similar approach is used for processing infrared images from Hubble’s Near Infrared Camera and Multi-Object Spectrometer (NICMOS). Infrared images taken with two or three filters are assigned red, green, and blue values based on their relative wavelengths. Thus the shortest infrared wavelength is shown as blue; the longest infrared wavelength is shown as red.

Separate filter images: grayscale



Separate filter images: colorized



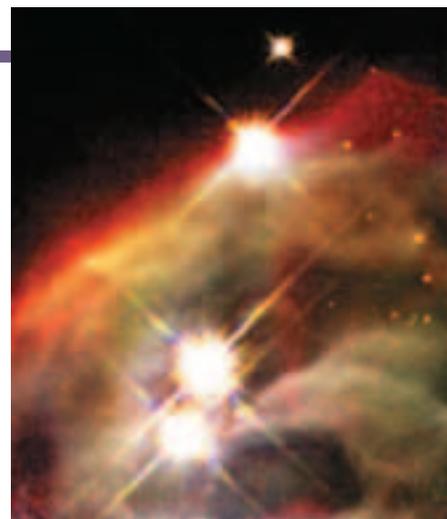
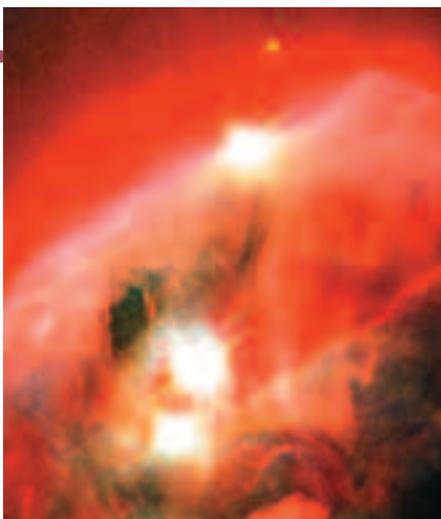
Building up the Eskimo Nebula, layer by layer. Four monochrome HST views through different color filters are each assigned a representative color similar to those the human eye would see. The colors are then stacked to produce this breathtaking scene.

Resulting composite image



ZOLTAN LEVAY (STSC)

The Near Infrared Camera and Multi-Object Spectrometer (NICMOS) was brought back to life in March during the most recent Hubble servicing mission. With a new cryogenic refrigerator cooling its onboard detectors, NICMOS is providing infrared views of many sights Hubble had already made famous in visible light. Here is a 50-arcsecond piece of the tip of the Cone Nebula as seen by Hubble's Advanced Camera for Surveys (*left*) and NICMOS. Stars hidden by opaque nebulosity at visible wavelengths shine through in longer-wavelength infrared light.



NASA/NICMOS GROUP

False Color

We sometimes use “color mapping” (or “paint by numbers”) to display a black-and-white image with colors that are completely unreal, because it is easier to distinguish small variations in hue than it is to see small differences in gray values. Here the colors displayed do not represent anything to do with color at all, rather different brightness levels. Choosing a color palette that is both useful for this purpose and visually pleasing can be a challenge. We try to avoid too psychedelic a treatment and stay with a more subdued monochrome tint for black-and-white images. A simple red color palette seems to bring out much more subtle details than you would see in shades of gray.

This approach, also dubbed “false color,” is further confused by the fact that some scientists refer to anything other than calibrated, photometrically correct color images as “false” color. And, if you translate ultraviolet or infrared into the visible color channels, that too is sometimes referred to as false color, even though it shows true wavelength differences. The terminology is something of a minefield and to the layman implies chicanery!

From Cosmetics to Cosmology

After a full-color image is assembled, we use *Photoshop* to remove seams between CCD chips. The pixels along the boundaries between each CCD must be carefully knitted together. Many of the ACS and WFPC2 images are assembled from multiple chips and must be mosaicked. In particular, the ACS's

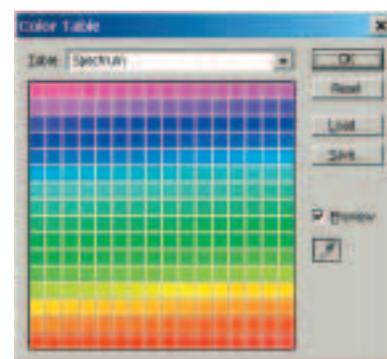
high efficiency allows it to be used for even wider mosaic imaging, say of a large galaxy like the magnificent M51.

Once an image is finalized and approved, it goes to our in-house photo lab, where carefully color-balanced prints are produced on giant processing machines; bigger enlargements are made individually by hand. Our Web site offers the full-resolution TIFFs and smaller JPEGs of the final products for download by the news media and astronomy enthusiasts.

For us it is a challenge and a privilege to work hard every day at sharing such fantastic new views of the universe with all humankind. And we're convinced the best is yet to come from Hubble. The ACS has fantastic capabilities — beyond everyone's expectations. In 2004 the Wide Field Camera 3 will be installed on Hubble, replacing WFPC2. It promises to have the broadest wavelength coverage of all the cameras, from near ultraviolet to near IR. It will also have the ACS's awesome, 0.05-arcsecond sharpness.

So stay tuned. Crisper and ever more colorful views from Hubble's “technicolor universe” are on the way. 

RAY VILLARD is the STScI News Director and a 15-year veteran of HST public outreach. He has written numerous popular astronomy articles, science radio scripts, and planetarium programs. ZOLT LEVAY joined STScI 19 years ago and has spent the past nine years producing images and online content for HST.



To create images that are as revealing as possible, the image processors at the Space Telescope Science Institute have stockpiled a few tricks. One of these is a protocol for false-color mapping of brightness levels, jokingly referred to as “paint by numbers.” Scientists first look at the image in black and white [1] and then as a negative print [2], where it may be easier to identify features. The most important shades of gray are identified [3] and assigned indexed colors [4], usually based on a red palette, to bring out nuances. This tactic is the true definition of “false color.”

