Colors of the Deep Sky

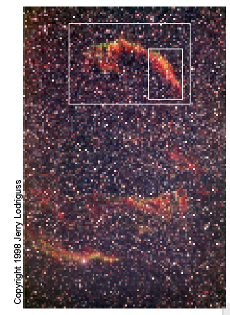
1. Some Types of Deep Sky Objects

This is how film records these objects.

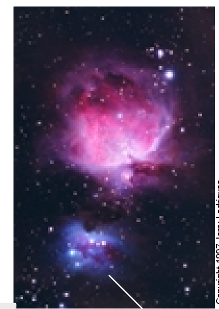
Double Cluster in Perseus

Stars, and star clusters

NGC 6960/6992/6995 Veil Nebula



M42, Orion Nebula



NGC 1975, a mix of emission regions (red) and reflection nebula (blue)

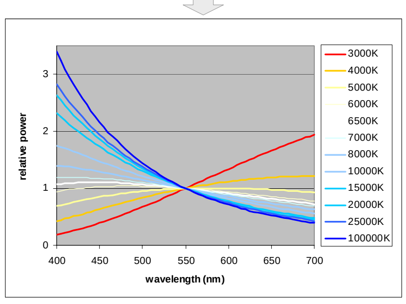
Emission nebula

Rho Ophiuchus region

Reflection nebula

Colors of the Deep Sky

2. Astronomical objects often have very simple, or at least well-known, spectra

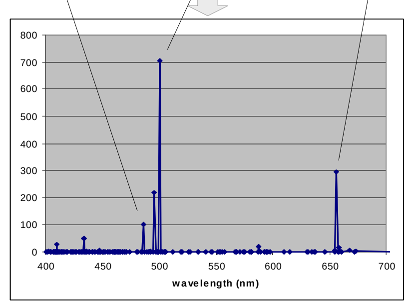


The spectral power distribution of most stars is dominated by the black body radiation of its surface, characterized by its temperature

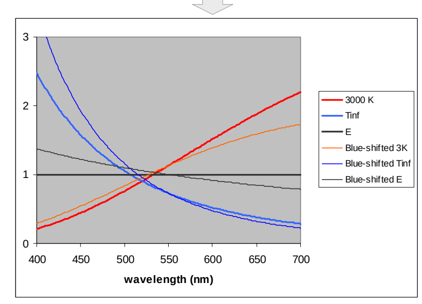
H-beta, emission line of Hydrogen at 486 nm.

O-III, emission line of twice-ionized Oxygen at 501 nm, 496 nm

H-alpha, dominant visible emission line of Hydrogen at 656 nm



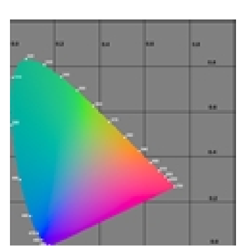
Emission nebulae are characterized by line spectra of energized gas. The spectrum of NGC 6543 (Cat's Eye Nebula) is shown here.

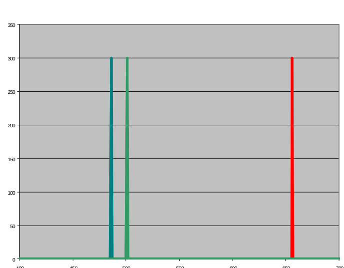


Reflection nebulae are regions of dust and gas that reflects the light from nearby stars. As a result, the reflected light is blue-shifted by scattering. Short wavelengths are reflected (scattered) more than long ones.

Colors of the Deep Sky

3. Human Visual System Response

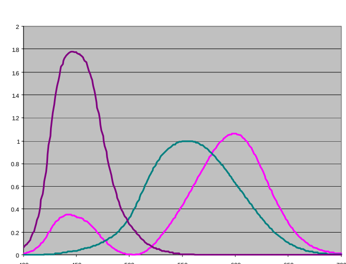




Object spectrum, $s(\lambda)$, in linear vector space notation: **f**

$s(\lambda) = \sum F_i f_i(\lambda)$

$f_i(\lambda)$ are the basis components of the spectrum, F_i are their amplitudes, (the components of vector **f**)



Human visual system sensitivity (color matching functions), $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$, linear vector space notation: **G**

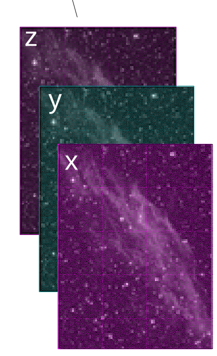
$g_{ij} = \int f_j(\lambda)\, \bar{x}_i(\lambda)\, d\lambda$

Note that matrix **G** depends on how we choose the basis functions to represent the spectrum

$$X = \int s(\lambda)\, \bar{x}(\lambda)\, d\lambda$$
$$Y = \int s(\lambda)\, \bar{y}(\lambda)\, d\lambda$$
$$Z = \int s(\lambda)\, \bar{z}(\lambda)\, d\lambda$$

$$\mathbf{e} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

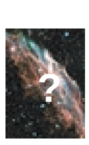
This is the tristimulus result we want to achieve when displaying an image of this deep sky object.



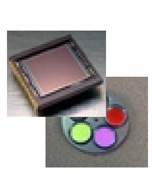
Tristimulus response
e = G f

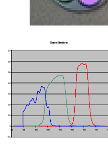
Colors of the Deep Sky

4. Typical Astronomical Imaging

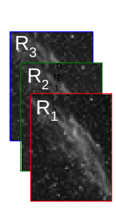


Object spectrum, $s(\lambda)$





Detector channel spectral sensitivity, $r_i(\lambda)$



r

Detector response

$R_i = \int s(\lambda)\, r_i(\lambda)\, d\lambda$

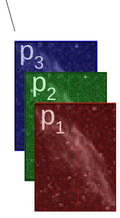
If the detector channels are used directly (e.g. film), the diagonals are 1. Sometimes "color balancing" is done to make the stars white, then the diagonals become unequal. Neither approach is correct.

$$\begin{bmatrix} a_{11} & 0 & 0 \\ 0 & a_{22} & 0 \\ 0 & 0 & a_{33} \end{bmatrix}$$

A

Gain matrix A represents direct coupling between detector channels and display channels

This is the RGB file that is displayed



p = A r

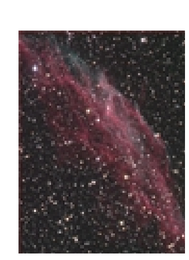
Display primaries

How the monitor phosphors present the RGB file, a conventional monitor transform to XYZ

$$\begin{bmatrix} 0.647 & 0.303 & 0.152 \\ 0.333 & 0.606 & 0.061 \\ 0.030 & 0.101 & 0.798 \end{bmatrix}$$

C

Display colorimetry



e = C p

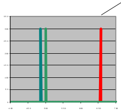
Visual result

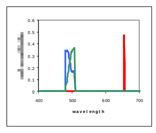
5. Calibrated Astronomical Imaging

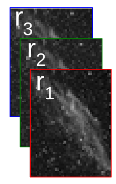
Colors of the Deep Sky

Part 1: Emission Nebula

This is the spectrum of the line emission regions of this image

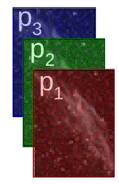






This is the matrix that will properly convert detector amplitudes to RGB display levels

$$\begin{bmatrix} 0.80 & -0.61 & -0.37 \\ -0.12 & 1.70 & 0.35 \\ -0.01 & -0.17 & 1.74 \end{bmatrix}$$



$$\begin{bmatrix} 0.647 & 0.303 & 0.152 \\ 0.333 & 0.606 & 0.061 \\ 0.030 & 0.101 & 0.798 \end{bmatrix}$$

Object spectrum, $s(\lambda)$

$s(\lambda) = \sum F_i f_i(\lambda)$

$f_i(\lambda)$ are basis functions, in this case:

$f_1(\lambda) = \delta(656nm)$
$f_2(\lambda) = \delta(501nm)$
$f_3(\lambda) = \delta(486nm)$

Detector channel spectral sensitivity, $r_i(\lambda)$. Narrowband filters provide the best signal-to-noise for line emitters

r

Detector response

$\mathbf{r} = \mathbf{H}\,\mathbf{f}$

$r_i = \sum F_j \int f_j(\lambda)\, r_i(\lambda)\, d\lambda$

$h_{ij} = \int f_j(\lambda)\, r_i(\lambda)\, d\lambda$

B

Colorimetric coupling between detector channels and display channels

$\mathbf{B} = \mathbf{C}^{-1}\,\mathbf{G}\,\mathbf{H}^{-1}$

p = B r

Display primaries

C

Display colorimetry

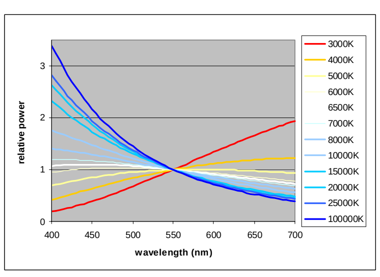
e = C p

Visual result

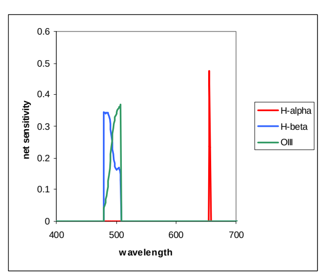
$\mathbf{e} = \mathbf{C}\,\mathbf{C}^{-1}\,\mathbf{G}\,\mathbf{H}^{-1}\,\mathbf{r}$
$= \mathbf{G}\,\mathbf{H}^{-1}\,\mathbf{H}\,\mathbf{f}$
$= \mathbf{G}\,\mathbf{f}$

6. Why are the stars blue-green in the calibrated emission image?

Colors of the Deep Sky



Stars are broadband emission sources. A typical star, say one with a temperature of 6500K, has a fairly uniform spectral power distribution (spd).



When measured by the three (narrow) passbands used in the emission nebula detector, stars will result in aproximately equal amplitudes in each channel.

If the gain-bandwidths of the three detectors were the same, and we measure a D65-type star, the relative detector response would be (1,1,1).

r = (1, 1, 1)

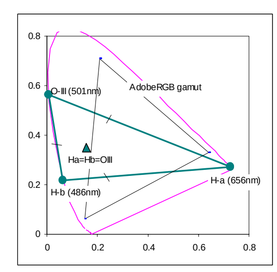
$X = 1 \cdot x_{656} + 1 \cdot x_{501} + 1 \cdot x_{486} = 0.265$

$Y = y_{656} + y_{501} + y_{486} = 0.594$

$Z = z_{656} + z_{501} + z_{486} = 0.846$

chromaticity (x,y) = (0.16, 0.35)

In the illumination model of three line sources, equal amplitudes of each will result in a color that is strongly blue-green.



The gamut of colors possible from the three line-emission sources is shown.

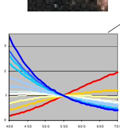
When there are equal-energy amounts of each primary, the result is a color that is outside of a typical RGB display gamut.

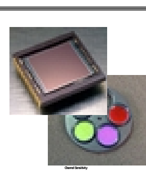
7. Calibrated Astronomical imaging

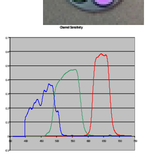
Colors of the Deep Sky

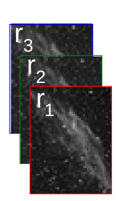
Part 2: Blackbody radiators

These are the spectra of the stars in this image

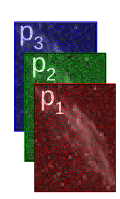








$$\begin{bmatrix} 2.47 & 1.24 & -0.35 \\ -0.09 & 2.99 & -0.51 \\ -0.10 & -0.38 & 4.12 \end{bmatrix}$$



$$\begin{bmatrix} 0.647 & 0.303 & 0.152 \\ 0.333 & 0.606 & 0.061 \\ 0.030 & 0.101 & 0.798 \end{bmatrix}$$

Object spectrum, $s(\lambda)$

$s(\lambda) = \sum F_i f_i(\lambda)$

For calibrating blackbody emitters, approximate their spectra using these basis functions:

$f_1(\lambda) = spd(3000K^0)$
$f_2(\lambda) = \sim E$ (makes whitepoint = E)
$f_3(\lambda) = spd(T_\infty)$

Detector channel spectral sensitivity, $r_i(\lambda)$ Wideband filters are used for broadband emission sources.

r

Detector response

$\mathbf{r} = \mathbf{H}\,\mathbf{f}$

$r_i = \sum F_j \int f_j(\lambda)\, r_i(\lambda)\, d\lambda$

$h_{ij} = \int f_j(\lambda)\, r_i(\lambda)\, d\lambda$

B

Colorimetric coupling between detector channels and display channels

$\mathbf{B} = \mathbf{C}^{-1}\,\mathbf{G}\,\mathbf{H}^{-1}$

p = B r

Display primaries

C

Display colorimetry

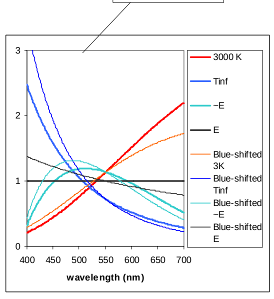
e = C p

Visual result

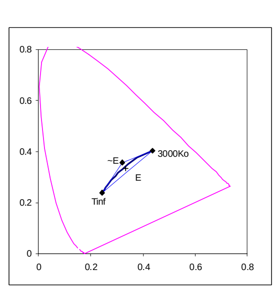
$\mathbf{e} = \mathbf{C}\,\mathbf{C}^{-1}\,\mathbf{G}\,\mathbf{H}^{-1}\,\mathbf{r}$
$= \mathbf{G}\,\mathbf{H}^{-1}\,\mathbf{H}\,\mathbf{f}$
$= \mathbf{G}\,\mathbf{f}$

Remember, **G** for this spectral basis is not the same as the **G** used for the emission line case (in section 5 above).

A blue-shifted version of these bases can be used to image reflection nebula.

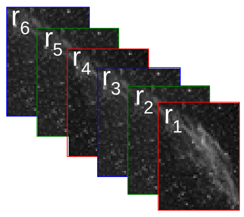


Here are plots of the basis functions used for approximating blackbody radiators.



The gamut of this basis set is a compact space that contains the blackbody emission locus

8. Simultaneous calibration of line and broadband emitters



Detector response

r = **H f**

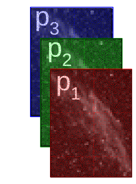
r has 6 detectors,
f now has 6 basis functions (lines plus blackbody bases),
H is 6x6

$$\begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} & b_{16} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} & b_{26} \\ b_{31} & b_{32} & b_{33} & b_{34} & b_{35} & b_{36} \end{bmatrix}$$

$\mathbf{B} = \mathbf{C}^{-1}\,\mathbf{G}\,\mathbf{H}^{-1}$

B is now 3x6.

G, the cross products between color matching functions and the basis functions is also 3x6



p = B r

Display primaries

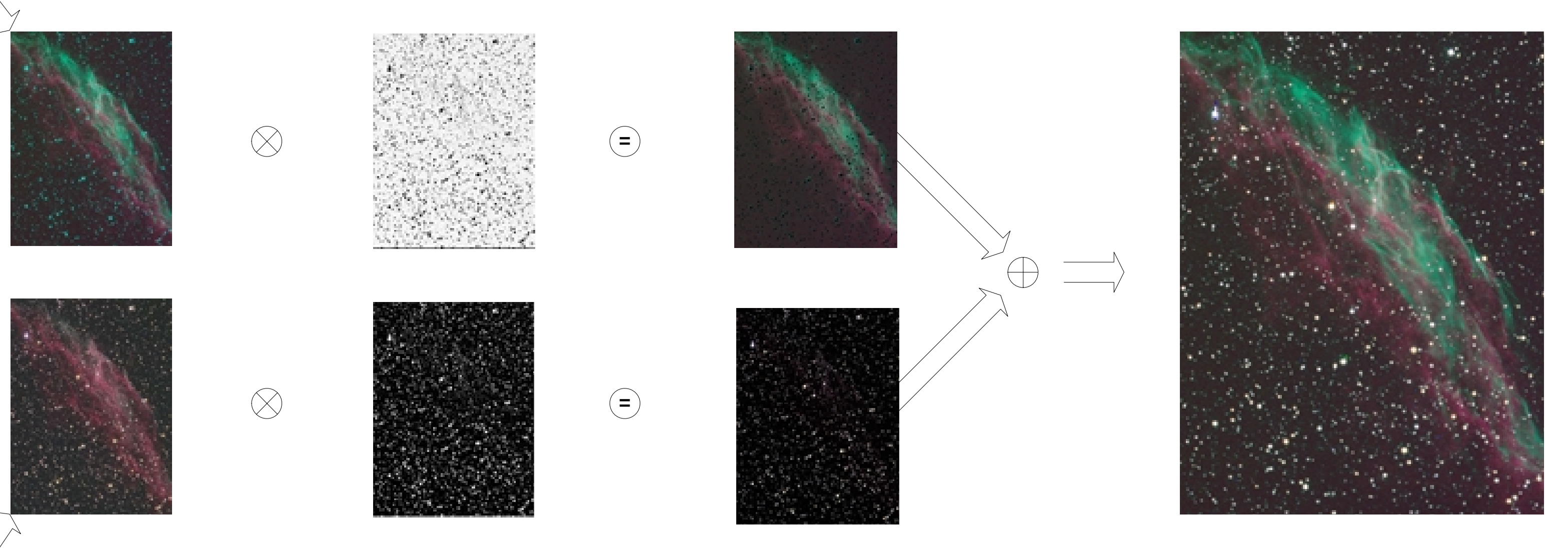
Three RGB components result
[3x1] = [3x6] * [6x1]

An unsuccessful result: the emission image is lost in the noise of the wideband sensors.

More work is needed to resolve the different signal-to-noise ratios of the various detector channels.

Colors of the Deep Sky

9. Combining individually calibrated images



Create median mask for use as spatial filter

Weight each image by its mask and superpose them

The result is a correctly rendered emission nebula in a field of correctly colored stars!

A full-resolution, colorimetrically rendered image of NGC 6995, the Veil Nebula

10. Some Examples

"Press release" images

N.A.Sharp, REU program, National Optical Astronomy Observatory/Association of Universities for Research in Astronomy/National Science Foundation

"This image was made by combining a number of exposures taken on the night of July 15th 1996, with a 2048x2048 CCD detector at the Burrell Schmidt telescope of the Warner and Swasey Observatory of Case Western Reserve University (CWRU), situated on Kitt Peak in southern Arizona."

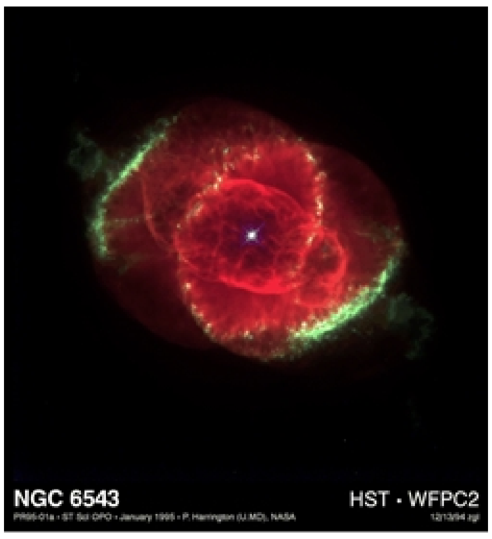
The color characteristics are typical of RGB exposures which have been color balanced for the stars.

Colorimetric renderings

Mike Cook

SBIG ST-10 sensor on an Astrophysics 130mm f/6 refractor from his suburban driveway (Huntertown IN). He has fitted his filter wheel with the CFW8 red, green, blue wideband filter set, and also has installed three narrowband filters to record spectral emission lines H-alpha (656nm), ionized oxygen OIII (501nm) and H-beta (486nm).

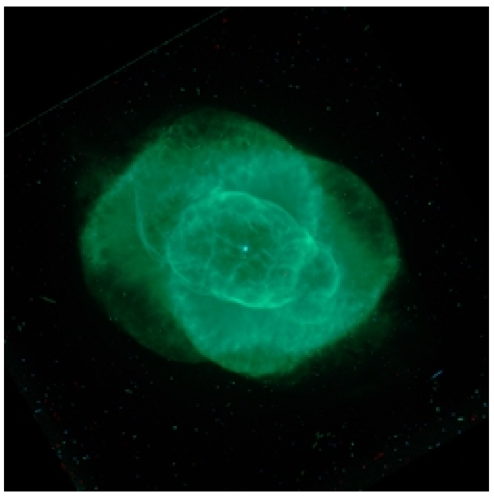
Image calibrated using methods described in this paper.



"*This color picture, taken with the Wide Field Planetary Camera-2, is a composite of three images taken at different wavelengths. (red, hydrogen-alpha; blue, neutral oxygen, 6300 angstroms; green, ionized nitrogen, 6584 angstroms).*"

NGC 6543 is also known as the Cat's Eye Nebula.

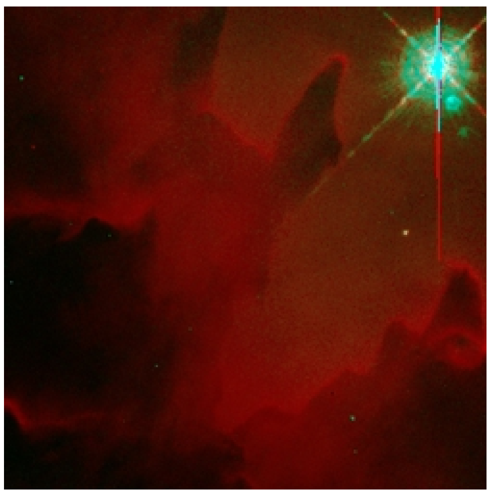
All three of these wavelengths are strongly red, but when assigned to different color channels, creates a pseudocolor image that helps astronomers visualize the chemistry and physical processes going on.



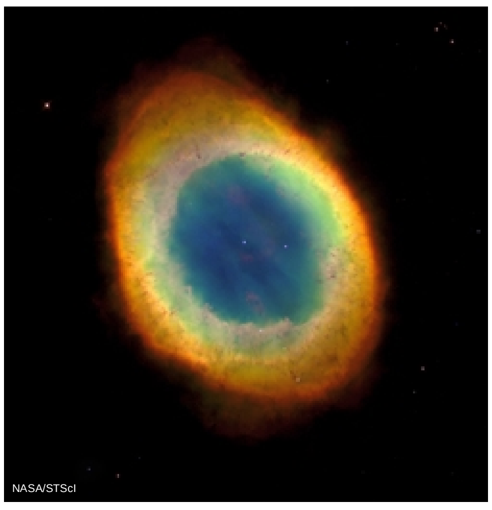
The strongest emission lines in the Cat's Eye Nebula are H-alpha, O-III, and H-beta (see the spectrum at section 2 of this poster). Hubble Space Telescope image frames from the Wide-Field Planetary Camera-2 corresponding to these lines were colorimetrically combined to obtain this "true color" view of the nebula. Although there is is significant red H-alpha energy, it is not enough to bring the combination with blue-green O-III into the RGB display gamut, and so the result is a nearly monochromatic structure in the characteristic blue-green of O-III. The bright dots and streaks in the image are artifacts from cosmic ray hits during the exposure.

Credit: Jeff Hester and Paul Scowen (Arizona State University), and NASA

"The picture was taken on April 1, 1995 with the Hubble Space Telescope Wide Field and Planetary Camera 2. The color image is constructed from three separate images taken in the light of emission from different types of atoms. Red shows emission from singly-ionized sulfur atoms. Green shows emission from hydrogen. Blue shows light emitted by doubly- ionized oxygen atoms. "

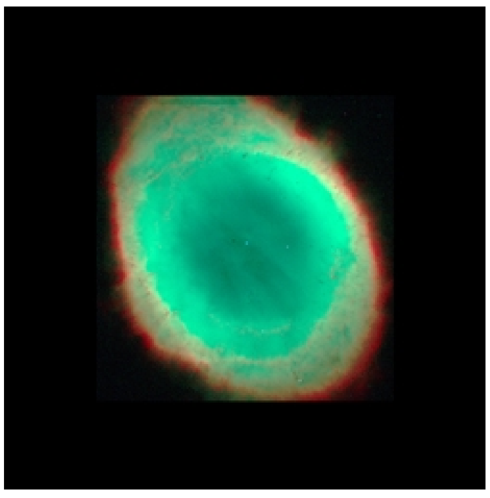


The same S-II (673nm), H-alpha (656nm), O-III (501nm) WFPC2 image channels for a region of this famous Hubble picture, colorimetrically combined. The area is bathed in the strong glow of Hydrogen.



"The NASA Hubble Space Telescope has captured the sharpest view yet of the most famous of all planetary nebulae: the Ring Nebula (M57). In this October 1998 image, the telescope has looked down a barrel of gas cast off by a dying star thousands of years ago. This photo reveals elongated dark clumps of material embedded in the gas at the edge of the nebula; the dying central star floating in a blue haze of hot gas. The nebula is about a light-year in diameter and is located some 2,000 light-years from Earth in the direction of the constellation Lyra.

"The color image was assembled from three black-and-white photos taken through different color filters with the Hubble telescope's Wide Field Planetary Camera 2. Blue isolates emission from very hot helium, which is located primarily close to the hot central star. Green represents ionized oxygen, which is located farther from the star. Red shows ionized nitrogen, which is radiated from the coolest gas, located farthest from the star. The gradations of color illustrate how the gas glows because it is bathed in ultraviolet radiation from the remnant central star, whose surface temperature is a white-hot 216,000 degrees Fahrenheit (120,000 degrees Celsius). "



A colorimetric rendering of the same N-II (658nm), H-a (656nm), O-III (501nm), and He-II (469nm) emission lines in the Ring Nebula. The blue helium line is so weak that it contributes virtually nothing to the image, leaving the blue-green O-III to dominate until the very edge of this nebula. Not as pretty perhaps as the NASA promotional picture, but color-correct!