The Global Color of Pluto from New Horizons

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Abstract

The New Horizons flyby provided the first high-resolution color maps of Pluto. We present here, for the first time, an analysis of the color of the entire sunlit surface of Pluto and the first quantitative analysis of color and elevation on the encounter hemisphere. These maps show the color variation across the surface from the very red terrain in the equatorial region, to the more neutral colors of the volatile ices in Sputnik Planitia, the blue terrain of East Tombaugh Regio, and the yellow hue on Pluto’s North Pole. There are two distinct color mixing lines in the color–color diagrams derived from images of Pluto. Both mixing lines have an apparent starting point in common: the relatively neutral-color volatile-ice covered terrain. One line extends to the dark red terrain exemplified by Chthulhu Regio and the other extends to the yellow hue in the northern latitudes. There is a latitudinal dependence of the predominant color mixing line with the most red terrain located near the equator, less red distributed at mid-latitudes and more neutral terrain at the North Pole. This is consistent with the seasonal cycle controlling the distribution of colors on Pluto. Additionally, the red color is consistent with tholins. The yellow terrain (in the false color images) located at the northern latitudes occurs at higher elevations.

Key words: Kuiper belt objects: individual (Pluto) – planets and satellites: surfaces

1. Introduction

Investigations of Pluto’s color at visible wavelengths have progressed from color photometry of the combined light of Pluto and Charon, to color maps from the mutual transits and occultation of Pluto and Charon (Binzel 1988; Young et al. 2001), to Hubble Space Telescope observations in different passbands resulting in maps (Buie et al. 2010). In 2015, New Horizons provided the first high-resolution color imaging of Pluto (Stern et al. 2015). This paper describes the color of Pluto from the highest resolution color images recorded by the spacecraft.

The color images were taken with the Ralph instrument (Reuter et al. 2008), which has two focal planes: (1) the Multi-spectral Visible Imaging Camera (MVIC) and (2) the Linear Etalon Imaging Spectral Array (LEISA). A single telescope with a beamsplitter (at 1.1 μm) sends light to each of the focal planes. MVIC has seven separate detectors, six time-delay integration (TDI) CCDs, and one frame transfer CCD. Four of the TDI CCDs are used for color observations; the other focal planes provide panchromatic imaging capabilities. When a color observation is executed, New Horizons data are recorded from all four color TDI arrays simultaneously. Each TDI array has 32 × 5000 optically active pixels (Reuter et al. 2008). There are three broadband channels: blue, red, near-infrared, and a narrow band methane channel (Table 1). The narrow band channel is called the methane channel because it is sensitive to methane ice absorptions at 890 nm. The responsivity of each of the MVIC channels is described in Howett et al. (2017).

2. Observations

The New Horizons mission began observing Pluto in color in 2015 April, more than three months before the closest approach to Pluto. The observations from 2015 April to mid June did not resolve the disk of Pluto, but they did provide global color of Pluto over multiple rotations at a unique phase angle (15°) not obtainable from Earth. This paper focuses on the 17 color images taken with MVIC within the last approximately 5.5 days on approach to Pluto (see Table 2). Each line in the table describes an observation that is a single MVIC TDI scan that covered Pluto. Most of these observations additionally included Charon and some observed Nix.
and Hydra as well. Other papers by Howett et al. (2017) and Grundy et al. (2016) describe the color of Charon and a mechanism to explain its red North Pole. The colors of the small satellites have been discussed in Weaver et al. (2016).

The Request ID in Table 2 is an identifier of the observation used in planning the observing sequence. The first four letters PEMV stand for Pluto Encounter MVIC observation. The next two digits are the visit number, which indicate if this is a

Table 1
Filter Passbands

| Filter            | Wavelength Range, nm |
|-------------------|----------------------|
| Blue              | 400–550              |
| Red               | 540–700              |
| Near-infrared (NIR)| 780–975             |
| Methane           | 860–910              |
repeated observation (note that two of the observations are repeated to give increased observations of a particular longitude). The next letter sequence gives the intended targets of the observation: PC stands for Pluto and Charon, and PCNH stands for Pluto, Charon, Nix and Hydra. The remainder of the Request ID indicates the purpose for the observation: mapping, time resolution, or color imaging. The Mission Elapsed Time (MET) in the table is a counter on the spacecraft that increments each second since launch and provides a unique timestamp for the data. The image scale on the surface of Pluto ranges from 127 km/pix to 660 m/pix across this data set. The Ralph electronics side used for each observation is given in the last column of Table 2. The Ralph instrument has redundant electronics that are denoted Side 0 and Side 1. To provide redundancy in our observation planning, we generally alternated which electronics side was powering the instrument for each observation.

The first 16 observations in Table 2 are displayed in Figure 1 and the last observation in the table is shown separately in Figure 2 because it is the highest resolution color image of Pluto. These images are enhanced color (not natural color as perceived by the human eye) using the three broadband filters of MVIC. The changing sub-spacecraft longitude over this sequence of images is due to the rotation of Pluto about its spin axis, which has a period of approximately 6.4 days. This sequence of observations covers about 280° of sub-spacecraft
longitude. The dark area at the bottom of the first image (PEMV_01_PC_MULTI_MAP_B_5) is Cthulhu Regio (some Pluto surface feature names are informal and others are formal), which can also be seen at the lower left in the highest resolution images. A color map of Pluto with latitude and longitude markings and feature names is provided in Figure 3. The color stretch of the Pluto map (Figure 3) was chosen to enhance the color differences across different color units and is different from the color stretch of Figures 1 and 2, which simply used the I/F from the blue, red, and NIR observations in the blue, green, and red color channels.

3. Reduction

The raw images from the spacecraft were processed using the following steps.

1. The raw images have a bias level subtracted from the raw counts. The bias level is a fixed number that depends on the focal plane array and electronics side used for the observation and is given in Table 3.

2. Each row of the image is divided by a one-dimensional flat-field array (5000 elements long) to remove flat-field effects. The bias subtracted and flat-fielded images are archived on the Planetary Data Systems Small Bodies Node.
Figure 4. The color–color plots from 16 Pluto images. The color–color plots correspond to the images in Figure 1. For each pixel in the image, color ratios are plotted (NIR/red vs. red/blue). The neutral-color point is indicated by the black circle at the intersection of the lines. In the upper left of each panel is the line number from Table 2. The color of each point represents the ratio of I/F in the methane channel to the I/F in the NIR channel. Blue indicates more methane.

Table 4
Gain Correction Factors

| Request ID | MET            | Gain Factor from Charon | Gain Factor from Pluto | Electronics Side |
|------------|----------------|-------------------------|------------------------|------------------|
| 2          | PEMV_01_PC_MULTI_MAP_B_6 | 298766878 | 0.917 | 0.909 | 1 |
| 4          | PEMV_01_PC_MULTI_MAP_B_9  | 298853048 | 0.929 | 0.930 | 1 |
| 5          | PEMV_02_PC_MULTI_MAP_B_9  | 298853218 | 0.956 | 0.963 | 1 |
| 7          | PEMV_01_PC_MULTI_MAP_B_12 | 298939128 | 0.922 | 0.910 | 1 |
| 8          | PEMV_02_PC_MULTI_MAP_B_12 | 298939298 | 0.954 | 0.940 | 1 |
| 10         | PEMV_01_PC_MULTI_MAP_B_15 | 299025878 | 0.922 | 0.908 | 1 |
| 12         | PEMV_01_PC_MULTI_MAP_B_18 | 299079028 | 0.919 | 0.905 | 1 |
| 14         | PEMV_01_PC_MULTI_LONG_1d2 | 299127628 | 0.945 | 0.952 | 1 |
| 16         | PEMV_01_PC_COLOR_1       | 299162518 | 1.036 | 1.048 | 1 |
| 17         | PEMV_01_P_COLOR2         | 299178098 | N/A  | 0.960 | 1 |
3. Model and remove the low-level (approximately 2 DN) pattern noise. The noise has a striped pattern that aligns with the row direction of the detector locally, but it is not consistent across the whole field of view. Using the pixels adjacent to the Pluto image, a model for the pattern noise can be determined and removed. Note that Pluto is typically between 20 and 700 DN in blue images and brighter in the other broadband filters (red and NIR), so the pattern noise is a small fraction of the total signal.

4. Convert the signal from DN to I/F using the method described in Howett et al. (2017). There are different radiometric calibration keywords that could be used when converting to I/F that depend on the color of the terrain. For this analysis, we have used the RSOLAR keyword, which is an approximation.

MVICs four color CCDs are adjacent to one another on the focal plane, and thus they do not image the same field of view. Through scanning, they cover the same field of view, but not simultaneously. At the usual scan rate of 1045 rad s$^{-1}$, it takes six seconds to sweep all four CCDs across a point in the target scene. The finite scan rate combines with spacecraft and target motion so that each of the MVIC colors images a point on the target from a slightly different point of view, so the geometry is a little different. Thus, each color channel is treated as an independent instrument and registered to the relevant Pluto and Charon base maps separately (Schenk et al. 2016). After they are all registered to the base map, they can be reprojected to a common geometry. To perform this task, we used version 3.5.0.7383 of the Integrated Software for Images and Spectrometers (ISIS3) package from the United States Geological Survey and selected the geometry for the BLUE filter as our target geometry for each scan. As this involves resampling, we sub-sampled to a finer grid approximately a factor of two finer than the original pixel scale to minimize loss of spatial information.

On approach to Pluto, we discovered that the gain of the NIR channel on the side 1 electronics is not consistent from observation to observation. The gain is consistent over a single image but varies from image to image at the 5%–10% level. For the first 16 images of Table 2, Charon appears in all of the images and could be used as a standard. The color of the terrains on Charon is longitudinally uniform and could be used to determine the gain offset using the Side 0 image taken before or after the Side 1 image with unknown gain. This was achieved by first computing and saving red/NIR and red/blue ratios for every Charon pixel in all Side 0 images on approach. An empirical model of the two-dimensional distribution of red/NIR and red/blue ratios for all Charon hemispheres is built by passing these Side 0 ratios through a Gaussian Kernel Density Estimator. Correction terms were found computing the red/NIR and red/blue ratios for the Charon pixels in any given Side 1 image, and finding a scaling factor on the Red/NIR ratio ($c = \text{Red/NIR}$) that maximized the likelihood that this sample of ratios was drawn from the empirical model.

The highest resolution Pluto color image did not have Charon in the field of view; therefore, the same approach used deriving a Charon-based correction term was used, but with color ratios drawn instead from Pluto’s terrains. To determine the consistency of this approach, we calculated these Pluto-derived correction terms for all Side 1 color images in Table 2 to compare the results of this method to the Charon deduced adjustment factors for the gain. They demonstrate excellent consistency. The results are shown in Table 4.

4. Analysis

Each pixel in the resolved images of Pluto has a different incidence and emission angles. This initial analysis of Pluto color focuses on what we can learn from color ratios because
the color ratio is less dependent on the directional scattering properties of the surface elements. Figure 4 displays the color–color diagrams for the first 16 Pluto images in Table 2. For each pixel in the image, the ratio of the NIR filter I/F to red filter I/F is plotted against the ratio of the red filter I/F to the blue filter I/F. Only pixels with an incidence and emission angle less than 80° are included in the diagrams.

Pixels that are more red from 400–700 nm fall to the right of the vertical line denoting a neutral red/blue ratio. Almost all pixels across all Pluto terrains visible to New Horizons are red in the wavelength range of 400–700 nm. Pixels that are more red from 540 to 975 nm fall above the horizontal line denoting a neutral NIR/red ratio. The color of each point in the figure is the ratio of I/F in the methane channel to the I/F in the NIR channel.

While the terrain on the Charon-facing hemisphere of Pluto (panels 4 and 5 of Figure 4, sub-spacecraft longitude near 0°) has dark Maculae spanning the globe just south of the equator.

Figure 6. A mosaic of color–color plots for the highest resolution color image of Pluto. The color of each point represents the ratio of the I/F in the methane filter to the I/F in the NIR filter, as shown in the color bar. Blue points indicate a lower ratio for the I/F of methane to NIR, which is consistent with absorption by methane ice at 890 nm. Each panel is a color–color plot from the observation PEMV_01_P_COLOR2 displaying a different range of ratios for methane to NIR. Pixels that have the methane to NIR ratio in the range from 0.50 to 0.84 are displayed in the upper right. The panels increase in methane to NIR ratio from left to right and top to bottom.

Figure 7. Left: the color–color diagram for PEMV_01_P_COLOR2 with selected pixels on the diagram indicated in black. Right: the PEMV_01_P_COLOR2 image with the selected pixels from the color–color diagram indicated in white. These pixels are representative of the neutral end member in the predominant color mixing line. The sharp edge at the lower right of the globe is a result of only considering pixels with an emission angle < 80°.
Meng-p’o, Hun-came, and Vucub-came Maculae, those terrains are less red than the reddest terrain in Cthulhu Regio. This can be seen by comparing the extent of the points in the color–color diagram across the 16 images. In panels 4 and 5, there are very few pixels (as a fraction of the total) with color ratios greater than 1.4 in both axes, compared to both panels 16 and 1. To explicitly remove the effect of different spatial resolution, Figure 5 shows a comparison of color–color plots from three different observations (separated by approximately 120° of longitude) after downsampling the later two observations to the spatial resolution of the first image. Comparing the color–color plots from these three observations shows that the encounter hemisphere (anti-Charon face of Pluto) has the most red terrain on Pluto with the NIR/red ratio reaching 2 and the red/blue ratio reaching 1.8 even in the downsampled image. The western part of Cthulhu Regio is visible in observation PEMV_01_PC_MULTI_MAP_B_6, and this terrain is red, but as seen in Figure 5, the color is not as extreme as the red color seen in the non-Charon hemisphere of Pluto at closest approach.

The color–color plot for the highest resolution Pluto image is shown in Figure 6 with each panel displaying different values of the methane I/F to NIR I/F ratio, hereafter referred to as methane to NIR ratio. The terrain with the smallest ratio of methane/NIR likely have methane on the surface due to absorption by methane ice at 890 nm. These pixels are blue from 540–975 nm (below the horizontal line) and red from 400–700 nm (to the right of the vertical line). This corresponds
to the areas of central and south Sputnik Planitia (north Sputnik Planitia is more red) and the mid-latitudes, regions both known to be nitrogen-rich with small amounts (0.1% to 1%) of methane from LEISA infrared spectroscopy (Schmitt et al. 2017). In contrast, the color–color units with the highest methane/NIR ratio, which have no significant absorption at 890 nm, are located in the upper right of the color–color plot. This corresponds to the dark red near-equatorial regions.

There are what appears to be two distinct color mixing lines in the color–color plots. The steeper-sloped color mixing line comprises the bulk of the pixels on Pluto and the less-stEEP slope color mixing line corresponds to the yellow regions concentrated near Pluto’s North Pole.

First we consider the steep-sloped mixing line. The end members of this color mixing line are the high albedo icy terrain (Figure 7) and the dark red terrains of Cthulhu Regio (see Figures 8 and 9). The intermediate pixels along the primary color mixing line correspond to the less red terrain to the north and south of Cthulhu Regio, see Figure 10. For each of these figures, the globe and color–color diagram have been constructed from the image after binning over 3 × 3 pixel boxes.

As shown in Figure 7, the more neutral-color end member spans southern Sputnik Planitia, the mid-latitude icy terrains, and the valley extending into Pluto’s North Pole. The red end of this color mixing ratio is the central region of Cthulhu Regio (Figure 8). The concentric region around the center of Cthulhu Regio has a location along this mixing line abutting the most red terrain (Figure 9). The color of the red terrain is consistent with the presence of tholins as inferred from infrared spectroscopy of Pluto from New Horizons (Protopapa et al. 2017). While tholins can exhibit different colors depending on the initial composition and the irradiation history, they are typically a dark red. Using the reflectivity of an Ice Tholin sample (Cruikshank et al. 2016), we computed the I/F color ratios for red/blue to be 2.49±0.61 and for NIR/red to be 2.25±0.31 and these value are consistent with the red end member of the steep-sloped mixing line. The error estimates for the color ratios of the laboratory samples were constructed from the uncertainty in reflectivity of Ice Tholin.

The distribution of the red terrain is likely the result of Pluto’s insolation cycle at seasonal and longer timescales. This region never experiences darkness through a full Pluto rotation at any point in Pluto’s precessional cycle, thus plausibly reducing the opportunity for deposition of volatile ices (nitrogen, methane, and carbon monoxide) at that latitude (Binzel et al. 2017). The color gradient across Cthulhu Regio is consistent with the idea of seasonal insolation gradients causing the color variation because the most red terrain is located nearest to the equator. Figure 11 shows a histogram of the color ratio (NIR/red) for the pixels of PEMV_01_P_COLOR2 as a function of latitude. For this figure, the pixels below −2 km elevation were excluded to remove the pixels from Sputnik Planitia (SP). SP is a basin and volatile ices condense preferentially in the basin (Bertrand & Forget 2016).
Figure 12. Left: the color–color diagram for PEMV_01_P_COLOR2 with selected pixels on the diagram indicated in black. Right: the PEMV_01_P_COLOR2 image with the selected pixels from the color–color diagram indicated in white. This yellow terrain is located near Pluto’s North Pole. The selected pixels fall on the less-steep-sloped color mixing line.

The basin disrupts the general trend of color with latitude and is therefore excluded from the histogram in Figure 11. The most red terrain (indicated by red in the histogram and corresponding to an NIR/red ratio > 2) only occurs near the equator; the next most red terrain (indicated in pink and with an NIR/red ratio between 1.5 and 2.0) is also found predominantly near the equator.

Next, we consider the less-steep color mixing line. Figure 12 shows selected points on this mixing line and the corresponding points on the color image. This terrain is associated with a yellow color near Pluto’s North Pole that extends southward to the northeast margin of SP. This color mixing line is evident in all of the color–color plots of Figure 4 because the North Pole of Pluto is visible in all of these images.

The yellow coloring agent is likely distinct from the dark red coloring agent that dominates Pluto’s surface because of the distinct population of pixels on the two color mixing lines. This yellow color unit is generally associated with higher elevation terrain (discussed more below). This color unit is correlated not only with high elevations, but also with a high fractional abundance of CH₄:N₂ and a reduced fractional abundance of N₂:CH₄ (<20%) as shown in Figure 13 (Protopapa et al. 2017). The solid solution of CH₄ and N₂ can exist in a CH₄-rich state (CH₄:N₂) or in a N₂-rich state (N₂:CH₄; Protopapa et al. 2015).

The yellow coloring agent could be a photolysis product from different molecular reactants than the dark red products seen at more equatorial latitudes. Specifically, the North Pole region is depleted in nitrogen compared to more mid-latitudes, which show a combination of volatile ices including nitrogen and dark red materials. If the yellow material formed in place, it would require an energy source for the photolysis such as UV radiation or cosmic rays. At current atmospheric pressures, no significant UV radiation reaches the surface for photolysis to be an active process. Further analysis is needed to understand if photolysis could occur on the surface through UV solar radiation during periods of rarefied atmosphere or if cosmic rays could provide sufficient energy.

There is an unusual red color unit associated with low-latitude troughs. The most prominent example of this color unit is Virgil Fossa, but it can also be seen in Beatrice Fossa and another linear feature that is likely a topographic low, see the elevation map in the lower right panel of Figure 14. Note that the unusual red material is not present across all of Virgil or Beatrice Fossae, but it is localized in regions of these features, and the regions where the unusual red material is present correspond to the presence of water ice (Schmitt et al. 2017). Not everywhere that has water exhibits this unusual red color, but in all of these locations there is a combination of water and significant amounts of tholin.

Using a digital elevation map based on stereoscopic images from New Horizons (Schenk et al. 2016), the color of Pluto as a function of elevation can be examined. Figure 15 gives the color ratios for all pixels with incidence and emission angles less than 80° for PEMV_01_P_COLOR2 (unbinned). The color of the pixels represents the elevation of each surface element, ranging from ~5 km to +3 km. To see the details of the color ratios with elevation, color–color diagrams for each one-km step in elevation are shown in Figure 16.

The lowest elevation terrain (in the top two panels of Figure 16) is that of SP. The less-steep color mixing line is not evident until the elevation is more than ~2 km. For the highest elevation points, from +2 to +3 km elevation, the most dense region on the color–color diagram is the color mixing ratio corresponding to the yellow terrain.

There is a blue terrain that is most predominantly seen in the East Tombaugh Regio. This terrain is characterized by the presence of methane and a bluish color with color ratios: NIR/red < 0.97, red/blue < 1.15, and CH₄/NIR < 0.92. This blue terrain is also present at other longitudes just north of the equator in Figure 17.

5. Conclusions

There is large variegation across Pluto’s surface from the relatively blue terrain of the East Tombaugh Regio to the red of the Cthulhu Regio and the yellow of the North Pole. There is a general pattern of dark red material near the equator and bright, more neutral-colored materials near the pole, consistent with a volatile transport away from the equatorial regions that receive
Figure 13. The fractional abundance of the solid solution of CH₄ and N₂ from Protopapa et al. (2015). Left: the fractional abundance of the CH₄-rich state. Right: the fractional abundance of the N₂-rich state. The location of the yellow terrain coincides with the location of the CH₄-rich state of the solid solution of CH₄ and N₂.

Figure 14. Top left: the color–color diagram for PEMV_01_P_COLOR2 with selected pixels on the diagram indicated in black. Top right: the PEMV_01_P_COLOR2 image with the selected pixels from the color–color diagram indicated in white. This unique red color is predominantly found in the Fossae in this region on Pluto: (A and B) Virgil Fossae, (C) Beatrice Fossa, and (D) another linear topographic low feature. Lower left: topographic map of the region (Schenk et al. 2016); the terrain varies from −1.5 km to 2 km in elevation (dark is low elevation). Lower right: the enhanced color image of this region from PEMV_01_P_COLOR2.
Figure 15. Color ratios of pixels on the highest resolution Pluto image with each point color coded for elevation, as given in the color bar. The elevation ranges from $-5$ km to $+3$ km.

Figure 16. Color ratios of PEMV_01_P_COLOR2 as a function of elevation. The color ratios of Pluto terrain for $1$ km bins in elevation are shown. The lowest elevation from $-5$ to $-4$ km is displayed in the upper left. The highest elevation from $2$ to $3$ km is displayed in the lower right. The same color scale is used as in Figure 15.
more insolation on a seasonal timescale than the poles (Binzel et al. 2017).

Distinct color units correlate with certain topographic features such as the yellow terrain located at high latitudes and high altitudes. Another example is the unusual red terrain located at or near the equator and along troughs.

Pluto passed through equinox in 1989 and will reach northern solstice in 2029, with the next equinox in 2110. For approximately the next 100 years, Pluto’s icy North Pole will be in sunlight. Near northern solstice, it will be useful to observe the color of Pluto’s North Pole and compare to these observations to look for a change in the overall color of Pluto’s North Pole. This could constrain timescales for the processes affecting the color of Pluto’s surface, particularly the yellow unit at the North Pole.

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References

Bertrand, T., & Forget, F. 2016, Natur, 540, 86
Binzel, R. P. 1988, Sci, 241, 1070
Binzel, R. P., Earle, A. M., Buie, M. W., et al. 2017, Icar, 287, 30
Buie, M. W., Grundy, W. M., Young, E. F., Young, L. A., & Stern, S. A. 2010, AJ, 139, 1128
Cruikshank, D. P., Clemett, S. J., Grundy, W. M., et al. 2016, in LPSC, 1903, 1700
Grundy, W. M., Cruikshank, D. P., Gladstone, G. R., et al. 2016, Natur, 539, 65
Howett, C., Parker, A., Olkin, C., et al. 2017, Icar, 287, 140
Protopapa, S., Grundy, W. M., Reuter, D. C., et al. 2017, Icar, 287, 218
Protopapa, S., Grundy, W. M., Tegler, S. C., & Bergonio, J. M. 2015, Icar, 253, 179
Reuter, D. C., Stern, S. A., Scherrer, J., et al. 2008, SSRv, 140, 129
Schenk, P., Beyer, R. A., Moore, J. M., et al. 2016, AGUFM, P41C-03
Schnitt, B., Philippe, S., Grundy, W. M., et al. 2017, Icar, 287, 229
Stern, S. A., Bagenal, F., Ennico, K., et al. 2015, Sci, 350, aad1815
Weaver, H. A., Buie, M. W., Buratti, B. J., et al. 2016, Sci, 351, aae0030
Young, E. F., Binzel, R. P., & Crane, K. 2001, AJ, 121, 552