NICMOS/HST POST-PERIHELION IMAGES OF COMET HALE–BOPP IN OUTBURST

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Abstract. Near-infrared images of comet Hale–Bopp (C/1995 O1) were obtained from NICMOS/HST on UT August 27–28, 1997, when the comet emerged from the 50 degree solar elongation limit at 2.99 AU from Earth. Diffraction-limited images were obtained with camera 2 filters centered at 1.87, 1.90, 2.04 and 2.22 μm with $\sim$0.2$''$ resolution (0.076$''$/pixel; 165 km/pixel). Over the 1.7-hour baseline of observation, a recent (<7 hours) outburst is seen in the form of an expanding spiral arm with a projected expansion velocity of $\sim$80 m/s. Other asymmetric features include a jet emanating from the nucleus and several static linear features. Comparisons of the flux distribution in the 2.04 and 2.22 μm filters indicate that the region near the nucleus exhibits a slight, $\sim$3%, water ice absorption.

1. Introduction

With its unusually large and active nucleus, Comet Hale–Bopp (C/1995 O1) is an excellent candidate for high resolution imaging in the near-infrared from the Hubble Space Telescope (HST). These images offer high contrast between the coma and nuclear regions since contamination from reflected sunlight/fluorescence is at a minimum and thermal emission from dust peaks at longer wavelengths. Despite being unable to resolve the actual nucleus, such observations can penetrate the emissions from coma material to reveal details very near the nucleus at wavelengths sensitive to water vapor and water ice which are difficult to observe from the ground due to telluric absorption. This paper presents preliminary diffraction-limited (0.2$''$) images from the NICMOS instrument showing the comet in a post- perihelion outburst.

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2. Observations

NICMOS camera 2 imaged comet Hale–Bopp shortly after it emerged from the solar elongation limit (50 degrees) of the HST. The geocentric and heliocentric distances at this time were 2.992 and 2.486 AU, respectively. The phase angle at the comet was 18.5 degrees.

Images were obtained in four filters: F187N, F190N, F204M, and F222M. The first two filters sample opposite sides of the $\nu2 + \nu3$ band emission of water vapor. The F204M filter is centered on the potential absorption feature of water frost at 2.0 μm (Larson and Fink, 1977; Davies et al., 1997) whereas the F222M filter lies outside. Since the pixel scale of camera 2 (0.076″/pixel) provides Nyquist sampling of the diffraction-limit at wavelengths >1.8 μm, the images reported here are somewhat over-sampled. Nevertheless, they cannot resolve the expected nuclear diameter (40–80 km) since they correspond to only 165 km/pixel.

Twenty images were obtained sequentially in these filters during two separated segments: the first from UT 22:52 to 23:30 on 27 August 1997 and the second from UT 00:21 to 00:33 on 28 August 1997. Images of blank sky were obtained during the first sequence at 2.04 and 2.22 μm to subtract the effects of thermal background emission. All images utilized the “multiaccum” readout technique to facilitate cosmic ray rejection and to ensure high dynamic range. In each case the exposure time was 63.96 sec. The signal-to-noise of the brightest pixel in each of these exposures is $\sim$2000, where the standard deviation per pixel is measured on a blank sky exposure of the same length. Individual observations were also dithered to reduce the effects of bad pixels and cosmic rays. All images have been processed using the “calnica” procedure.

3. Results and Interpretation

3.1. Comet Hale–Bopp in Outburst(s)!

Figure 1 shows the complex morphologies observed at F222M at $\sim$UT 23:25. A bright nucleus is partially enveloped by a “spiral arm” with non-uniform surface brightness. The peak of the spiral feature is located 2400 km (1.1″) from the nucleus at a position angle of 257 E of N, but the spiral ranges in position angle between $\sim$190 and 320. A dark region is seen to the north of the nucleus, indicating a lack of reflecting particulates in that direction or possibly a shadow produced by the ejected material on the sunward side. The light we see is predominently scattered light from coma particles, rather than from reflection off the nucleus. The nuclear region itself is elongated horizontally by a short “jet” feature extending toward the east. This elongation is not caused by either cometary motion or telescope tracking since background stars exhibit linear trails of the expected diffraction width extending along the comet’s direction of motion to the SE. In addition, at least four long linear features extend across the full field-of-view (19.3″; 42,000 km projected separation). These features appear to penetrate into the nucleus in the NICMOS images, and are most easily seen in the unsharp mask image in Figure 2a. These linear features are evidently stable, as their position angles match those recorded by other observers in both pre- and post-perihelion images.

3.2. Temporal evolution

The "spiral arm" and "eastern jet" seen by NICMOS appear to be recent, and possibly on-going, outbursts of material. Over the time span of these observations, both features expand outwards with a projected velocity of $\sim$80 m/sec. This rate of expansion indicates that the outburst which formed the spiral arm occurred $\sim$7 hours earlier whereas the eastern jet may have begun only $\sim$2 hours earlier. In addition, the "spiral arm" structure was not apparent $\sim$19 hours earlier in "long pass" ($>$550 nm) images obtained by STIS (Weaver et al., 1997).

An outflow of material is illustrated in Figure 2b which shows the difference of two F222M exposures obtained 72 minutes apart. White corresponds to an increase of brightness with time while dark shows a decrease with time. The spiral arm both expands and diffuses with time while the eastern jet moves farther east (left). Note that the bright outer ring implies that the fastest-moving material has been ejected in a circular pattern, perhaps the result of looking down on a cone of material expanding away from the comet. Within a radius of 7″ from the nucleus, cometary material is expanding outward with clear evidence for a radial but apparently nonuniform outflow. Although the spiral feature fades with time, the integrated flux in a large (10″) aperture decreases by only $\sim$2% in all filters.

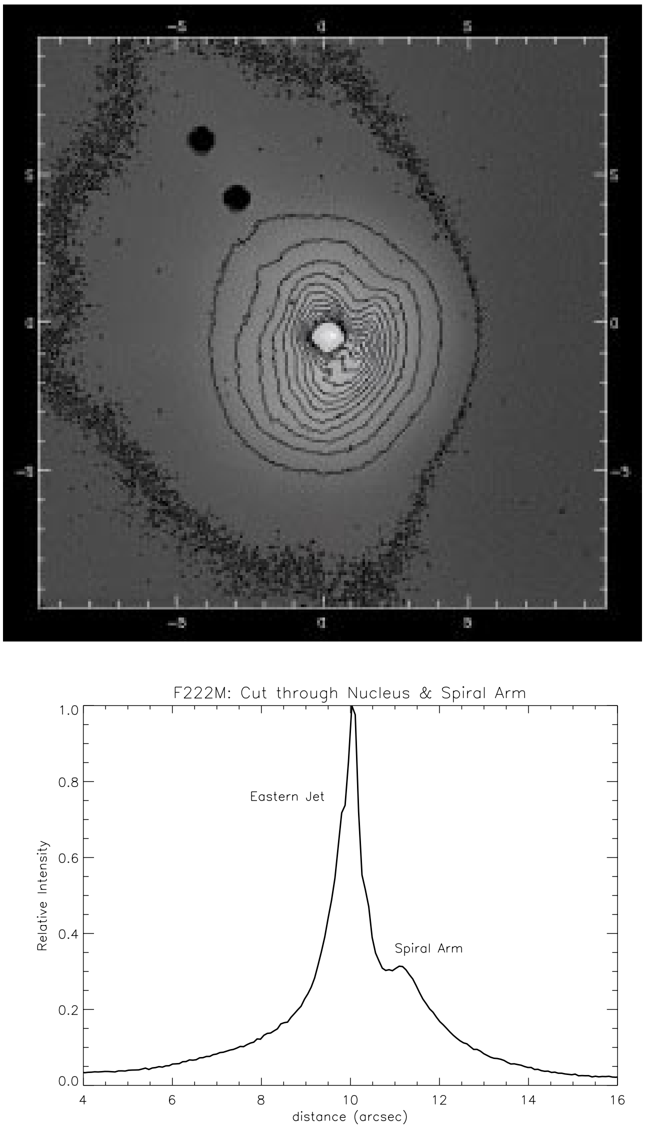
3.3. Spectral features

The images taken in the F187N and F190N filters are identical within the statistical errors; thus, a postulated excess of water vapor emission in F190N is negligible as compared to light scattered by dust.

The flux ratio of F204M/F222M could be sensitive to an absorption caused by water frost at 2.04 μm (Larson and Fink, 1977; Davies et al., 1997). In fact, there is evidence that this ratio is slightly depressed ($\sim$3%) within a radius of $\sim$1.9–2.3″ (4000–5000 km) from the nucleus. This analysis is still in progress and will be presented in a future publication.

3.4. Geometrical effects

For two reasons, the shape of the spiral feature is not likely to have been influenced by radiation pressure. First, even for dust particles as small as 1 micron, the force of radiation pressure at this heliocentric distance is small, yielding accelerations $\sim 10^{-4}$ m/sec^2. Second, the relative youth of this feature does not provide enough time for the effects of radiation pressure to accumulate even to the level of the



(a)

(b)

Figure 1. (a) Morphologies observed by NICMOS in Comet Hale–Bopp with filter F222M, shown in logarithmic contours. The plate scale is 0.076″/pixel (165 km/pixel) corresponding to a full field-of-view shown here of 19.3″. The scale marked on the figure is in arcseconds. North is 11.49 degrees clockwise of “up”. An expanding “spiral arm” (lower right) and “eastern jet”(elongation, ∼0.5″ left of nucleus) indicate recent and on-going outbursts. (b) A single pixel cut through the nucleus of a 63.96 sec. exposure with signal-to-noise 2000:1 at the nucleus and the intensity normalized to one. The “spiral arm” is the smaller peak, ∼1″ to the right of the nucleus. A slight bump to the left shows the “eastern jet”.

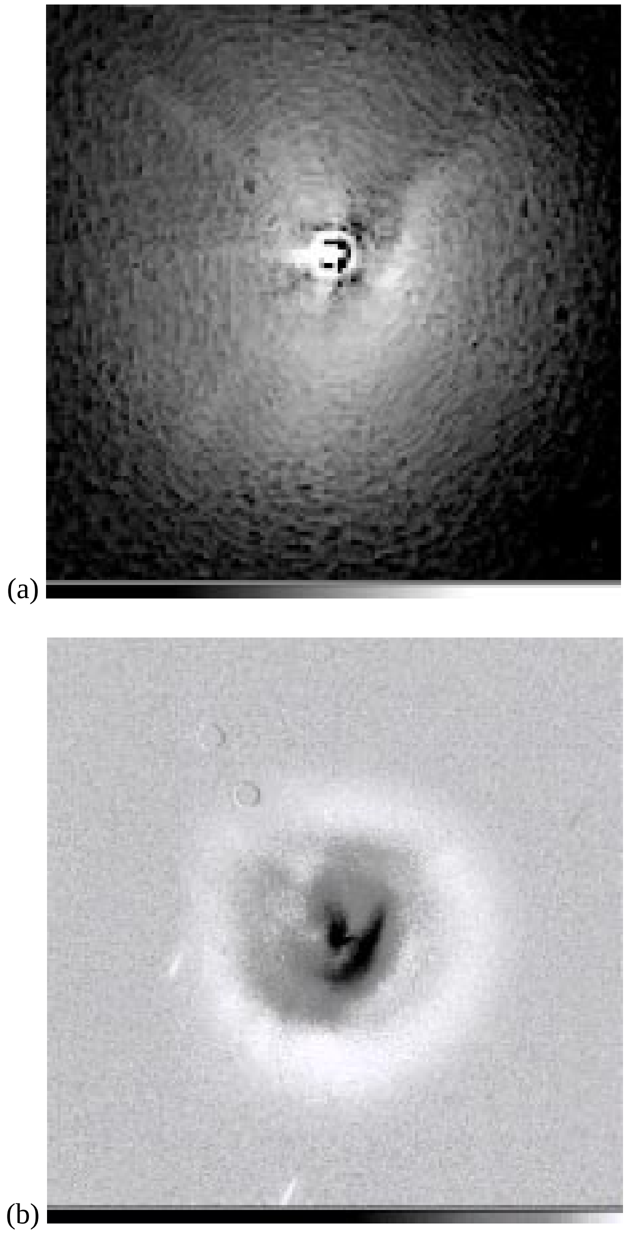


Figure 2. (a) Unsharp mask of the central 9.5″ showing linear features (including eastern jet) and spiral arm. This image was made by subtracting a smoothed (Gaussian with σ = 2 pix, then scaled by 0.95) image from the original F222M image. (b) Temporal effects of the outbursts are revealed in this difference of two F222M images taken 65 minutes apart. White shows an increase of brightness with time; dark a decrease. In both figures, North is 11.49 degrees clockwise of “up”.

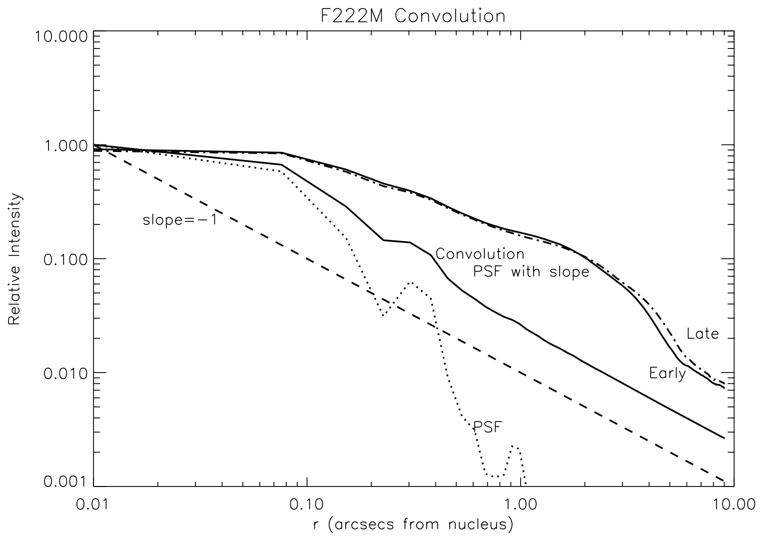


Figure 3. Azimuthally averaged radial surface brightness profile in filter F222M as a function of distance from the nucleus. The solid line marks the earliest observations and the dash-dot line shows the profile 72 minutes later. The dashed line represents a steady-state, isotropic outflow model with logarithmic slope = −1. The normalized point spread function profile is shown for comparison as a dotted line and the convolution of this with the model is marked by a solid line.

projected ejection velocity, ∼80 m/sec. Therefore, the spiral shape of this feature must be caused by the nature of the outburst and its location on the rotating comet.

Several research groups have established the rotational pole of comet Hale–Bopp (Kidger, 1998) near ecliptic coordinates (J2000) {315, −46}. At the epoch of the NICMOS observations, this pole position implies a viewing geometry nearly perpendicular to the rotational axis; i.e., looking down on the equator. This geometry makes it difficult to produce a spiral feature from a continuously erupting source located on a rotating comet. Instead we may be looking down on a cone-shaped "funnel" of material generated from an outburst of short duration directed toward the Sun. This model leads to strong foreshortening effects, implying that the actual dust velocities are much higher than the simple projected values. Such values are higher than those expected (∼80 m/sec) for this heliocentric distance (Sekanina, 1996).

Figure 3 presents the azimuthally averaged surface brightness profile in filter F222M for two observations separated by 72 minutes. The dashed curve models a steady-state, isotropic outflow from a point source with a logarithmic slope of −1 (Hanner, 1981; Campins et al., 1989). This simple model has been convolved with a measured point-spread function. Obviously this is a poor fit to the data, in contrast to the pre-outburst results obtained ∼19 hours earlier by STIS (Weaver, 1997). Instead the radial profile obeys the isotropic power law only at the very largest radii ($\geq 6''$) indicating that the outburst had not yet affected this material far from the nucleus. Clearly temporal variability and asymmetrical motions during an outburst complicate such modelling efforts. Evidence for radial expansion of material is again seen, as the early and late curves cross along the spiral arm feature.

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