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Radiative transfer model of the dust structures of CRL 2688

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Abstract. New Hubble images of the reflection nebula CRL 2688 from 0.6 to 1.6μm reveal significant variations of color and opacity in the distribution of scattered starlight. We have constructed a detailed radiation-transfer model consisting principally of an optically thick equatorial disk-like structure; bipolar lobes with density enhancements along the polar axis and at the base of lobes; an optically thin extended envelope containing spherical density-enhanced shells to mimic the outer rings of CRL 2688; and a pair of near-stellar caps that collimate and redden the dispersing starlight near its source. Our model nicely reproduces all of the basic features detected in the HST images, including the famous searchlights and arcs, as well as the measured spectral energy distribution ("SED") of CRL 2688. Assuming a distance of 420 pc we estimate the light originates in a giant star with a temperature $T \sim 7000$ K and a luminosity $L = 5500 \pm 1100$ L$_\odot$.

Keywords. planetary nebulae: general, planetary nebulae: individual (CRL 2688), circumstellar matter, reflection nebulae, radiative transfer

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The many delicate details of the pre-planetary nebula ("pPN") CRL2688 were revealed in HST images by Sahai *et al.* (1998) and Weintraub *et al.* (2000), including two bright N-S lobes and a surrounding system of arc-like rings. We obtained additional HST images in four broadband filters at 0.6, 0.8, 1.1, and 1.6 μm in order to study the color distribution of scattered stellar light throughout the nebula (Fig. 1). In this paper we present a model of radiation transfer that accounts very nicely for the observed distribution of reflected light, its color distribution, and the overall spectral energy distribution of CRL 2688.

CRL 2688 is illuminated solely by direct and multiply-scattered light from a carbon and nitrogen-rich supergiant of apparent spectral type F5 Ia with $T_{\rm eff} = 6500$ K (Klochkova *et al.* 2000; Cohen & Kuhi 1977; Crampton *et al.* 1975). Ueta *et al.* (2006) found that the lobes are inclined out of the sky by 7.7°, a distance of 420 pc, a stellar luminosity of 3160 L$_\odot$ from proper-motion measurements. We built an initial geometric model using these data and the geometric distribution of scattering and absorbing dust shown on the left side of Fig. 2.

We used the code LELUYA (www.leluya.org) that solves the integral equation of the formal solution of radiative transfer including dust scattering, absorption and thermal emission in two spatial dimensions. It uses a highly unstructured triangular self-adaptive grid. The geometry of the dust distribution, the attributes of the dust particles (size, scattering parameters, etc.), and the radiation temperature and luminosity were varied until the model results provided a good fit to the observed images and the spectral energy distribution ("SED") of CRL2688. We find a bolometric flux $= 1.0 \pm 0.2 \times 10^{-9}$ W/m^2 (luminosity $= 5500 \pm 1100$ L$_\odot$), an inclination angle $= 15°$, a dust condensation radius $= 46.4\,R_*$, and a stellar radius $R_* = 51 \pm 5$ R$_\odot$. The predicted color distribution and fits

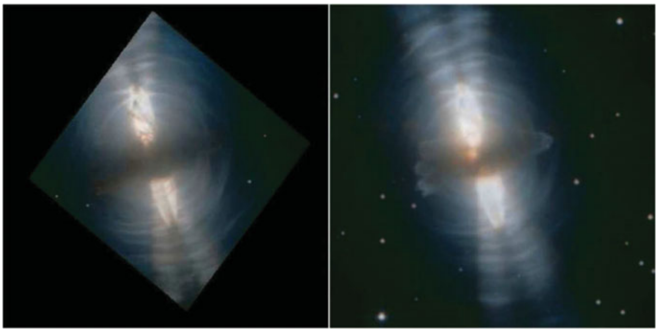

Figure 1. New HST images using WPC3 (Balick *et al.* 2011): Color overlays of the F606W-F814W (*left*) and F110W-F160W images (*right*) shown to the same scale and pixel size (0.″08) with a highly non-linear contrast function and exaggerated color saturation. The native resolutions of the images are 0.″040 (visible) and 0.″128 (IR). The field of view is 32″.

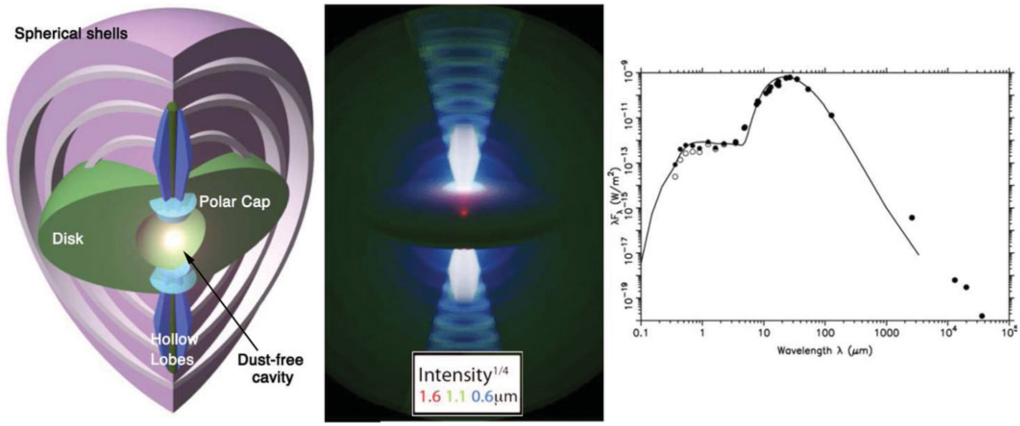

Figure 2. *Left*: geometric components of the model dust distribution. *Center*: predicted intensity and color distribution (4.5μm emission is overplotted in red). *Right*: fit of the predicted SED to the data.

to the SED are shown in the center and right panels of Fig. 2. The maximum dust temperature in our model varies between 1000 K and 1400 K, depending on the grain size, which rules out the maximum dust temperature of 330 K as suggested by Lopez & Perrin (2000).

The details of the model have been submitted to the ApJ for publication (Balick *et al.* 2011).

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