LONG-WAVELENGTH EXCESSES OF FU ORIONIS OBJECTS:
FLARED OUTER DISKS OR INFALLING ENVELOPES?

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ABSTRACT

The mid- to far-infrared emission of the outbursting FU Orionis objects has been attributed either to a flared outer disk or to an infalling envelope. We revisit this issue using detailed radiative transfer calculations to model the recent, high signal-to-noise ratio data from the IRS instrument on the Spitzer Space Telescope. In the case of FU Ori, we find that a physically plausible flared disk irradiated by the central accretion disk matches the observations. Building on our previous work, our accretion disk model with outer disk irradiation by the inner disk reproduces the spectral energy distribution between ~4000 Å and ~40 μm. Our model is consistent with near-infrared interferometry, but there are some inconsistencies with mid-infrared interferometric results. Including the outer disk allows us to refine our estimate of the outer radius of the outbursting, high mass accretion rate disk in FU Ori as ~0.5 AU, which is a crucial parameter in assessing theories of the FU Orionis phenomenon. We are able to place an upper limit on the mass infall rate of any remnant envelope infall rate to ~7 × 10−7 M⊙ yr−1 assuming a centrifugal radius of 200 AU. The FUor BBW 76 is also well modeled by a 0.6 AU inner disk and a flared outer disk. However, V1515 Cyg requires an envelope with an outflow cavity to adequately reproduce the IRS spectrum. In contrast with the suggestion by Green et al., we do not require a flattened envelope to match the observations; the inferred cavity shape is qualitatively consistent with typical protostellar envelopes. This variety of dusty structures suggests that the FU Orionis phase can be present at either early or late stages of protostellar evolution.

Subject headings: accretion, accretion disks — circumstellar matter — stars: formation — stars: pre–main-sequence — stars: variables: other

Online material: color figures

1. INTRODUCTION

The FU Orionis systems are a small but remarkable class of variable young stellar objects (YSOs) that undergo outbursts in optical light of 5 mag or more (Herbig 1977), with F−G supergiant optical spectra and K−M supergiant near-infrared (near-IR) spectra dominated by deep CO overtone absorption. FU Orionis objects (FUors) have been modeled as a high mass accretion disk around pre–main-sequence stars (Hartmann & Kenyon 1985, 1987a, 1987b) to explain the infrared color excesses and the variations of both the spectral type and rotational line width with wavelength (Hartmann & Kenyon 1996; Zhu et al. 2007, hereafter Paper I).

Herbig (1977) argued that at least some FU Orionis outbursts must be repetitive, and Hartmann & Kenyon (1996) suggested that this could be explained by infall from an envelope to the disk, replenishing the disk mass for further outbursts. The infall picture is also suggested by the presence of scattered light envelopes around FUors, suggesting that they are objects in early stages of star formation (Herbig 1977; Goodrich 1987). In the evolution sequence, FUors may play a significant role in transferring a large amount of mass (≥10%) to the central star, which is even higher than the mass accumulated in the T Tauri phase (Hartmann 1998).

However, not all FUors show the large mid-infrared (mid-IR) excesses that clearly demand dense infalling envelopes. In particular, Adams et al. (1987) suggested that FU Ori itself had only a depleted or low-density envelope. Kenyon & Hartmann (1991) suggested that a pure flared disk model could explain FU Ori while an infalling envelope was needed for V1057 Cyg, but Turner et al. (1997) proposed that both FU Ori and V1057 Cyg required flattened envelopes. Finally, taking advantage of IRS spectra obtained with the Spitzer Space Telescope, Green et al. (2006) concluded that the spectral energy distributions (SEDs) of V1057 and V1515 Cyg required envelopes and derived crude models for these objects, while FU Ori and BBW 76 might be explained with flared disks only. Some recent studies about the silicate features also show that FUors can be classified as two categories and some objects are evolved (FU Ori and BBW 76) with only disks left (Quanz et al. 2007).

The IRS spectra provide us with the opportunity to perform a much more detailed SED analysis for FUors. In Paper I, we developed detailed accretion disk models to study the inner disk of FU Ori and we derived an inner disk size ~1 AU. In this paper, we reexamine the interpretation of mid-IR excesses, taking advantage of the IRS spectra, with more detailed radiative transfer models, to resolve the disk/envelope problem. We will describe the observational data in § 2. In § 3, the method of calculating the temperature structure of the irradiated surface and the resulting spectrum is described. Model results for three FU Orionis objects (FU Ori, BBW 76, and V1515 Cyg) are presented in § 5. Finally, in § 6 we discuss some implications of our results.

2. OPTICAL AND INFRARED DATA

2.1. Photometry and Spectra

Because FU Orionis objects are significantly variable, it is crucial to minimize differences in the times of observations at