Photoevaporation of Protoplanetary Disks

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Introduction

The timescale at which a protoplanetary disk loses its primordial gas, which dominates the total disk mass, is a crucial factor regarding the outcome of the planet forming process in the vicinity of high mass stars. The photoevaporation of protoplanetary disks by external UV radiation in an environment dominated by high mass O-stars is a particularly potent mechanism for removing disk material. The timescale of photoevaporation is governed by the amount of UV radiation from the nearby O-stars, which significantly erodes the protoplanetary disk in less than a million years. Therefore, the presence of high mass stars might be lethal for forming planets since the EUV and FUV radiation of a nearby O-star can disrupt the protoplanetary disk on a short time scale (a couple of times 10^5 yr) and stop the planet formation process. On the other hand the radiation might trigger the formation of rocky planets by accelerating the dust settling and grain growth in the mid-plane of the disk. We reported the discovery of three comet like structures near different O-type stars (with the comet-like tails pointing away from the central high mass star) in 24 µm Spitzer/MIPS images (Balog et al. (2006); see Figure 1. for an example).

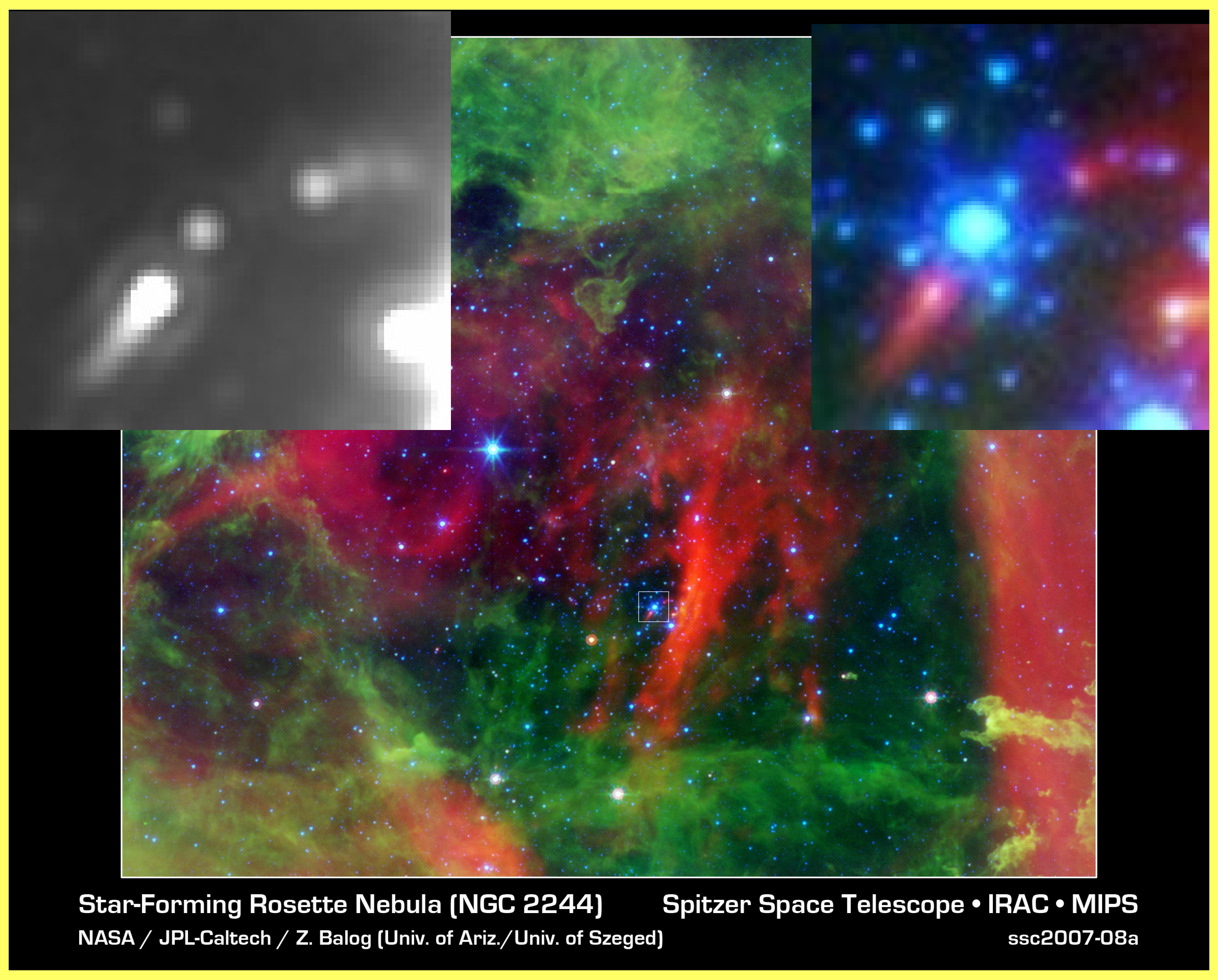
Star-Forming Rosette Nebula (NGC 2244) Spitzer Space Telescope • IRAC • MIPS
NASA / JPL-Caltech / Z. Balog (Univ. of Ariz./Univ. of Szeged) ssc2007-08a

Figure 1: *False color (R: 24 μm; G: 8 μm; B 4.5 μm) image of NGC 2244 containing one of our photoevaporating tails. The magnified areas in the corners of the image show the vicinity of the tail (designated with a white square) in color and in the 24 μm image.*

24 μm surface brightness profile

We reproduced the 24 μm surface brightness profile using a modified model of Su et al. (2005) (see Fig 2. and 3.). The models utilized optical constants for astronomical silicates and assumed a single grain size. It was found that the tail morphologies (faintness at 8 µm and the apparent lengths) placed strong constraints on the grain sizes. The minimum sizes were of order 0.01 µm in radius - smaller grains emitted too strongly at 8 µm to be included in the tails in significant numbers. Grains above 1 µm in radius tended to be too cold to fit the tail lengths.

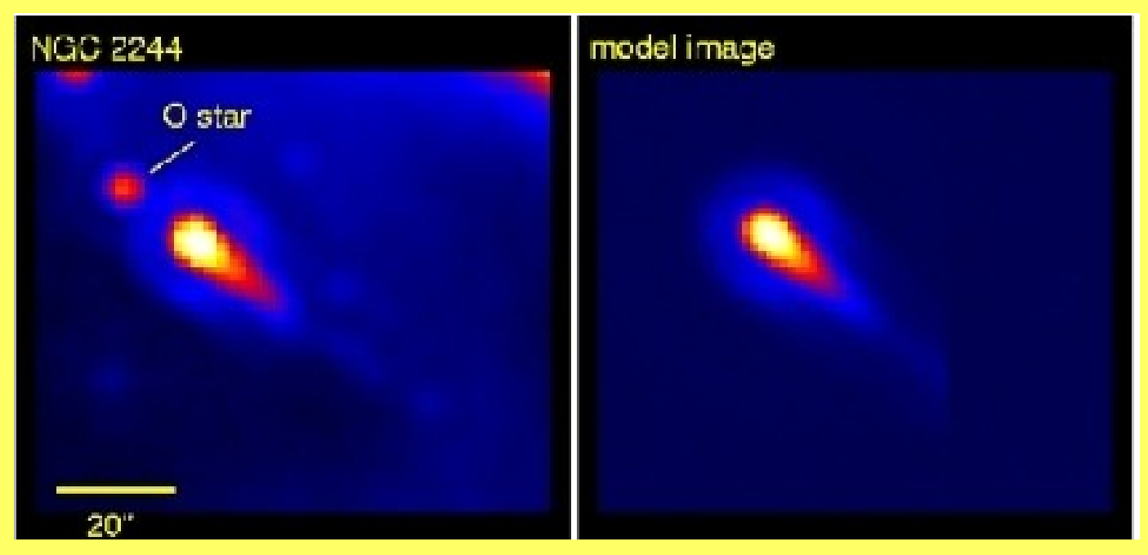

Figure 2.: *Real and model 24 μm image of the tail in Fig. 1*

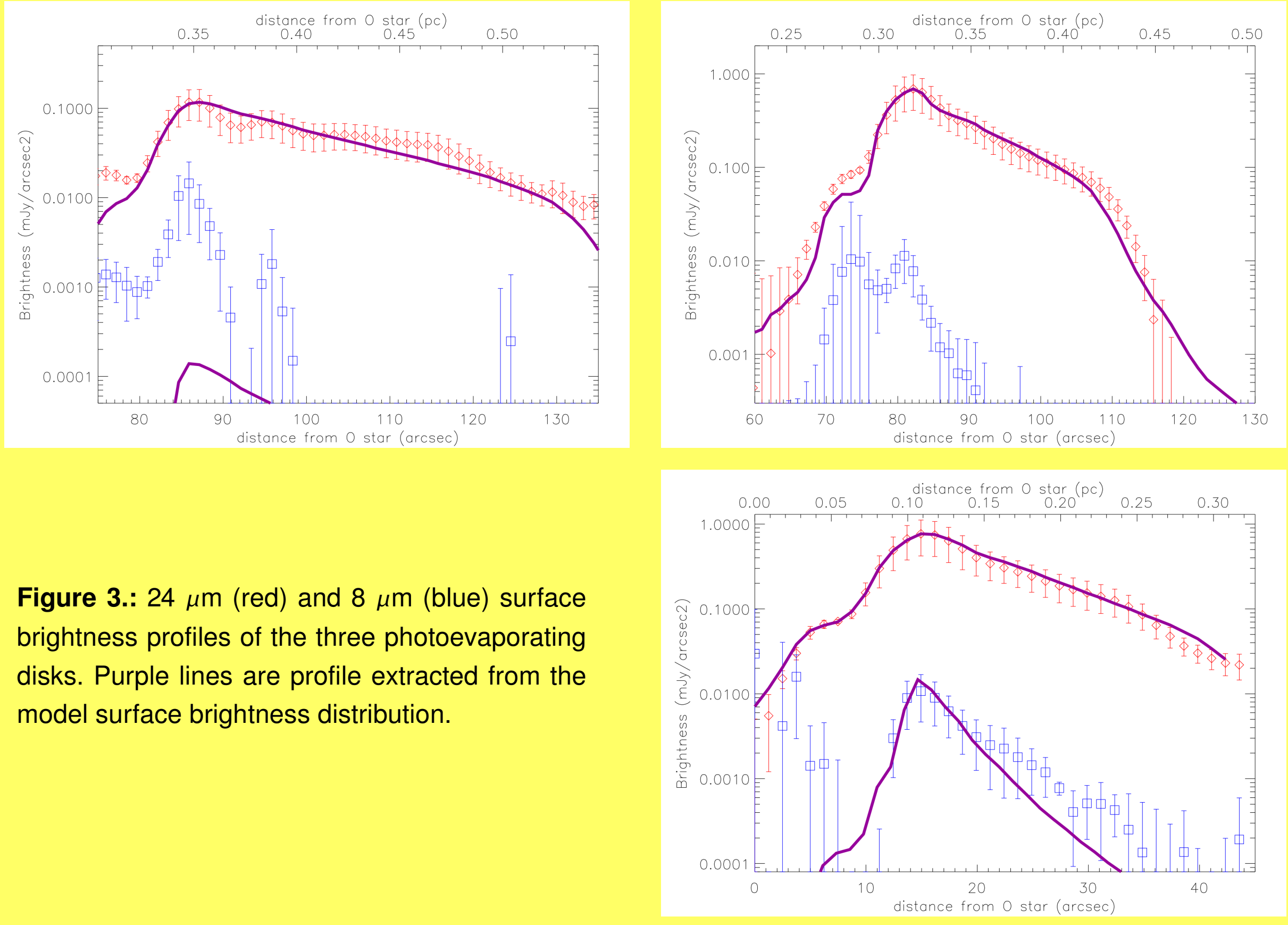

Figure 3.: 24 μm (red) and 8 μm (blue) surface brightness profiles of the three photoevaporating disks. Purple lines are profile extracted from the model surface brightness distribution.

Gas deficient tails

To investigate this phenomenon further and to get a better understanding of the nature of these objects, we have searched these three systems for the gas expected to be a significant component of the flow. We used Pα as an ideal tracer of the photoevaporation process, since it is the strongest emission line in the near infrared and is not strongly affected by extinction.

HST/NICMOS Pα observations show that the tails are extremely gas poor. As an example Fig. 4 shows the source in NGC 2244 at 24 µm, at 1.87 µm (Pα line) and in the continuum subtracted Pα images. The covered area is 19´´ × 19´´ (0.138 × 0.138 pc at the distance of NGC 2244). The observations indicate the tails are deficient in Pα emission by about a factor of one million compared to a simple model in which each dust tail contains a photo-ablating core of dense material (optically thick case). Our inferred gas mass upper limits for the optically thin case are at least two orders of magnitude lower than the gas masses expected in a typical T Tauri disk, implying gas to dust ratios 10^2 to 10^4 times lower than in the ISM .

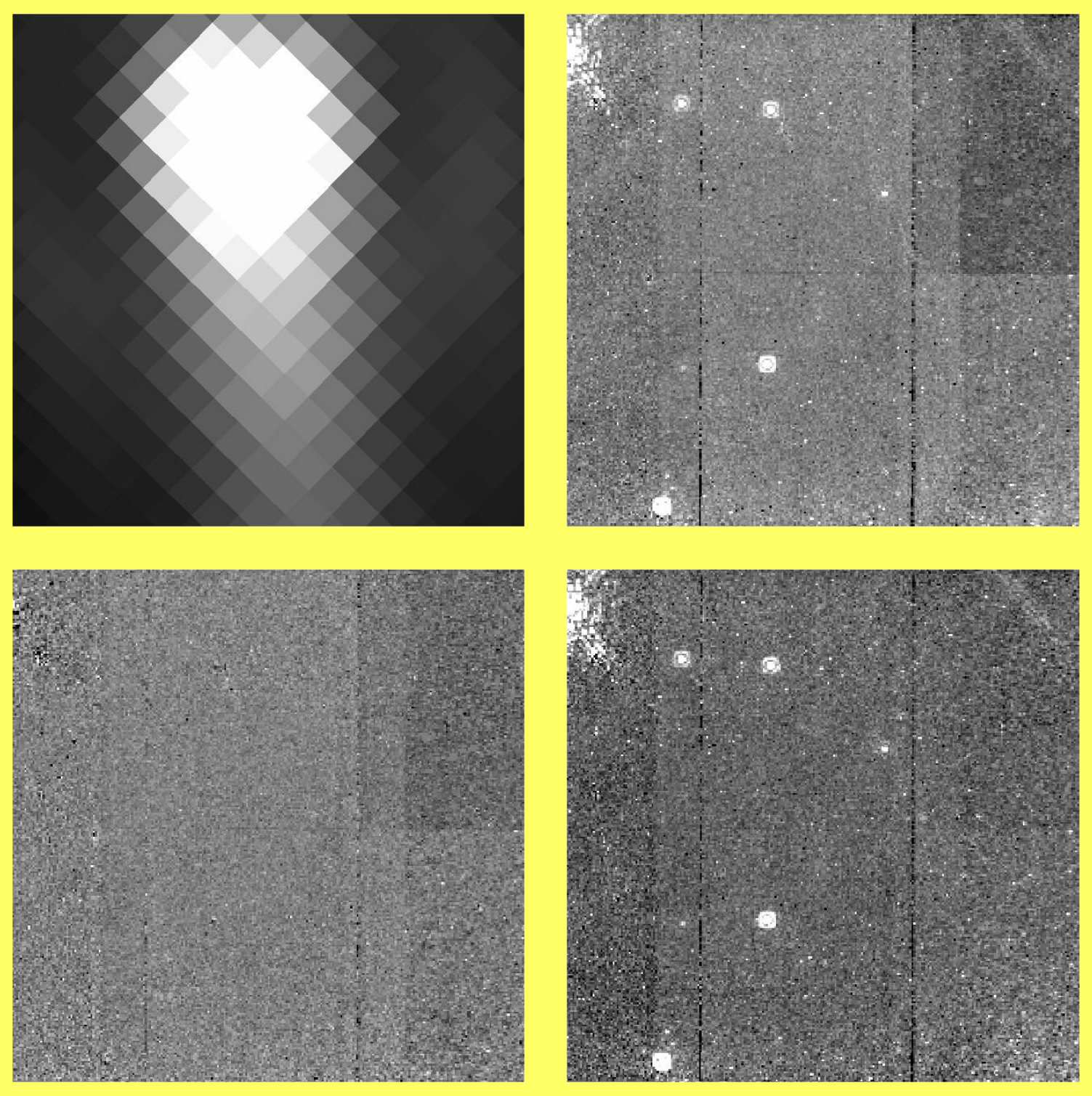

Figure 4. *MIPS 24 μm (upper left) HST/NICMOS Pa and continuum upper and lower right images and the continuum subtracted Pα image of the photoevaporating source in NGC 2244.*

References

Balog et al. 2006, ApJ, 605, L83
Balog et al. 2007, ApJ 660, 1352,
Balog et al. 2008, Apj, 688, 408
Su et al. 2005, Apj, 628, 487
Throop & Bally, 2005, ApJ, 623, L149

Spitzer/IRS spectra – SED – gas in the inner disk

We also report mid-IR spectra to provide a better understanding of the physical processes in the disk and to help determine the properties of the dust. We show our spectra in Fig. 5 along with the Kurucz model spectra for the stellar photospheres and our model SEDs of unbound small particles. The IR excess is clearly visible even in the low S/N low resolution spectra (see caption for the meaning of the symbols). The fit is satisfactory at wavelengths longer than 12 µm. At shorter wavelengths, there is significant emission from the "comet head" both from the stellar photosphere and from an excess bridging from 2.4 µm to 12 µm and centered on the head. The fits to tail spectra fall far short of accounting for the excess emission above the stellar photospheres in the 3 to 10 µm range, apparent in both our spectra and IRAC photometry. We conclude that these excesses indicate the presence of class II sources in the "heads" of our objects.

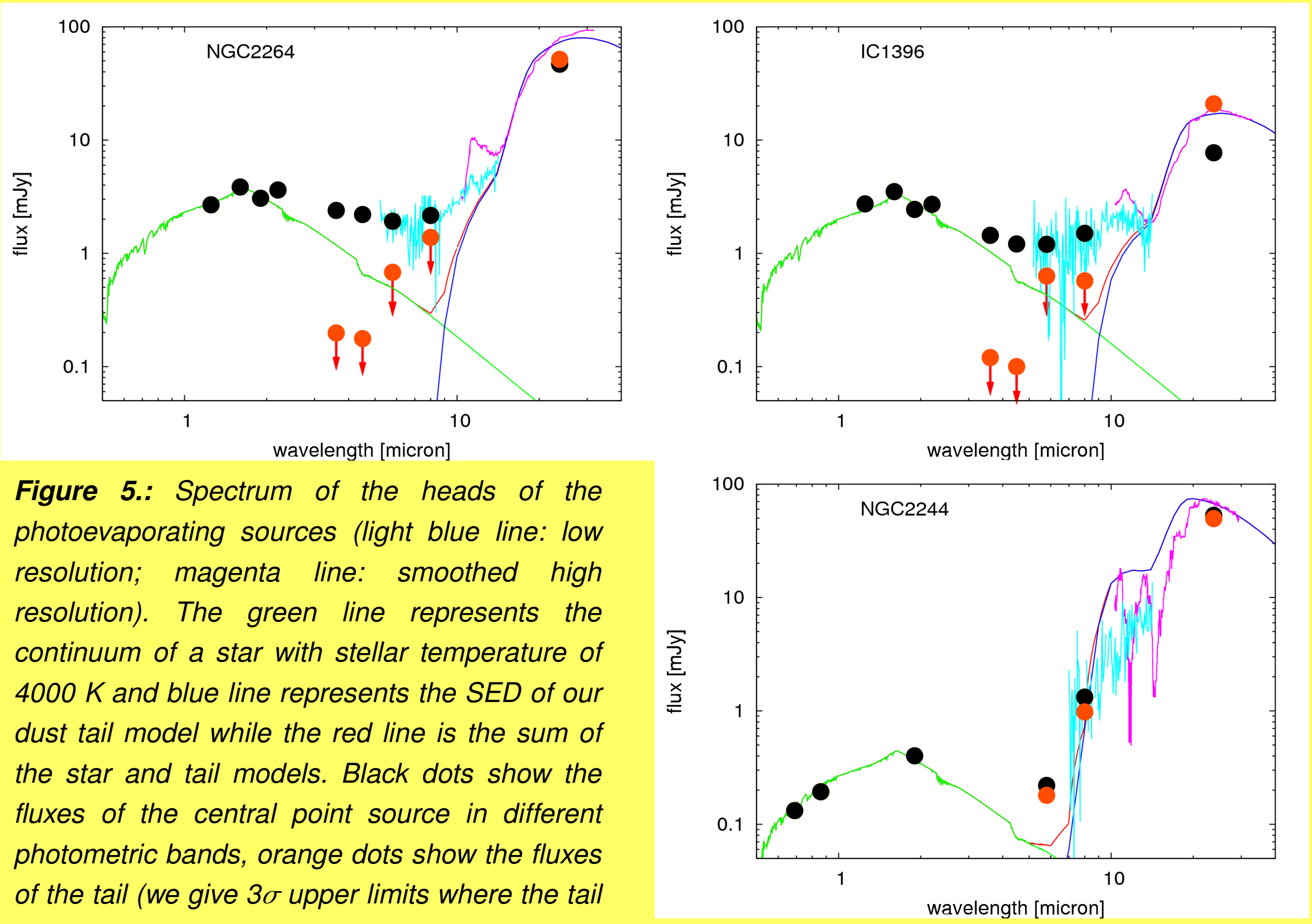

Figure 5.: *Spectrum of the heads of the photoevaporating sources (light blue line: low resolution; magenta line: smoothed high resolution). The green line represents the continuum of a star with stellar temperature of 4000 K and blue line represents the SED of our dust tail model while the red line is the sum of the star and tail models. Black dots show the fluxes of the central point source in different photometric bands, orange dots show the fluxes of the tail (we give 3σ upper limits where the tail is not detected).*

The origin of "comet" grains

The evaporation is powered by dust absorption of UV photons, followed by gas heating primarily by the photoelectric effect, with the resulting outflow of hot gas carrying along small, sub-micron sized dust grains. The larger dust grains will be left in a relatively gas-free environment. Throop & Bally (2005) show that these grains will be in an unstable configuration that will collapse to the disk mid-plane and that planet growth could be triggered as a result. There are other consequences. With the gas removed by photoevaporation in the outer part of the disk, its damping effects on grain motions (e.g., circularization of orbits) are also removed. Planetesimals will collide and initiate a vigorous episode of collisional cascades, that lead to a highly elevated rate of production of small, second-generation grains. These grains can be ejected by photon pressure due to photons from the O-star. This mechanism is a natural way to produce the large numbers of small grains required in our models of the infrared output of the tails of these sources. An additional driver for a large grain collision rate is the effect of photon pressure from the O-star perturbing the orbits of small grains that nevertheless remain gravitationally bound to the low mass star. The perturbed grains will be more likely to collide with others and initiate collisional avalanches that contribute substantially to the "comet tail".