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Chiaroscuro: From Pericenter Glow to Apocenter Enhancement - Illuminating Secular Structure of Dusty Planetary Systems

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Introduction

Asymmetries are often observed in circumstellar dust disks like β Pictoris, AU Microscopii, HD107146, etc. Two phenomena are often invoked to account these asymmetries:

1) Planetary perturbations, and
2) Asymmetric scattering of starlight by dust.

A disk's asymmetric appearance is also wavelength dependent. When viewed at infrared wavelengths, stellar heating of dust at periapse leads to the pericenter glow seen in infrared maps (Wyatt *et al.*, 1999), while optical maps of reflected starlight reveal an apocenter enhancement due to dust loitering at apoapse (Marsh *et al.*, astro-ph/0501140). Our aim is to assess these phenomena and to illustrate their effects in a circumstellar dust disk.

Planetary Perturbations

A broad circumstellar dust disk that harbors a planetary system tends to be disturbed by the planets' *secular* perturbations. To asses this, it is convenient to first transform a grain's orbital elements $(e, \varpi, i, \Omega) \longrightarrow (h, k, p, q)$ where

$$h = e\sin\varpi \quad k = e\cos\varpi \quad p = i\sin\Omega \quad q = i\cos\Omega \qquad (1)$$

The Lagrange planetary equations accounts for how a grain's orbit evolves due to perturbations from N planets:

$$\dot{h} = Ak + \sum_{j=1}^{N} A_j k_j \quad \dot{k} = -Ah - \sum_{j=1}^{N} A_j h_j \quad \dot{p} = \ldots \qquad (2)$$

where the A_j coefficients account for perturbations from planet j and A is the grain's free precession rate, with similar equations for the $\dot{p}$ and $\dot{q}$ (Murray & Dermott 1999). The solution to equation (2) are

$$h(t) = e_{free}\sin(At + \beta_{free}) + h_{forced}(t)$$

$$\text{where} \quad h_{forced}(t) = \sum_{j=1}^{N} C_j \sin(g_j t + \beta_i)$$

where the C_j depend upon the planets' masses and semimajor axes. The grain's free eccentricity e_{free} is due to its dispersion velocity, while $e_{forced} = \sqrt{h^2_{forced} + k_{forced}}$ is the forced eccentricity excited by the planets; ditto for the p's and q's. It is the forced orbit elements e_{forced} that govern the planetary disturbances seen in the disk face, while any vertical disturbances are due to the forced inclination i_{forced}.

Asymmetric Light Scattering by Dust

Dust is also an asymmetric scatter of starlight, which can also impart a brightness asymmetry in the disk. Light scattering is usually described with a Henyey-Greenstein phase function:

$$\Psi(\phi) = \frac{1 - g^2}{4\pi(1 - 2g\sin\phi + g^2)^{3/2}} \qquad (3)$$

where ϕ is the scattering angle and g is the scattering parameter (Hong 1985). Positive g indicates forward–scattering, while $g < 0$ indicates backscattering. Observations suggest that circumstellar dust tends to be forward–scattering, which makes the nearer parts of a dust–disk *brighter* that the more distant parts.

Caveats

This simple model is valid only if radiation pressure and Poynting-Robertson drag do not drive any significant radial drift. This implies that the dust sizes considered here are relatively large. This is probably the case for β Pictoris dust disk (Fig. 6), since dust–dust collisions are thought to destroy dust before PR drag causes their orbits to decay. But this is probably not the case at ϵ Eridani (Fig. 1), whose clumpy appearance is interpreted as due to dust delivered to mean motion resonances via PR drag (Kuchner and Holman 2003)—this phenomenon is not accounted for in our model.

Examples

Two dusty rings: ϵ Eridani which may be disturbed by an unseen planet, and HD 107146 whose brightness variations is believed due to asymmetric light scattering.

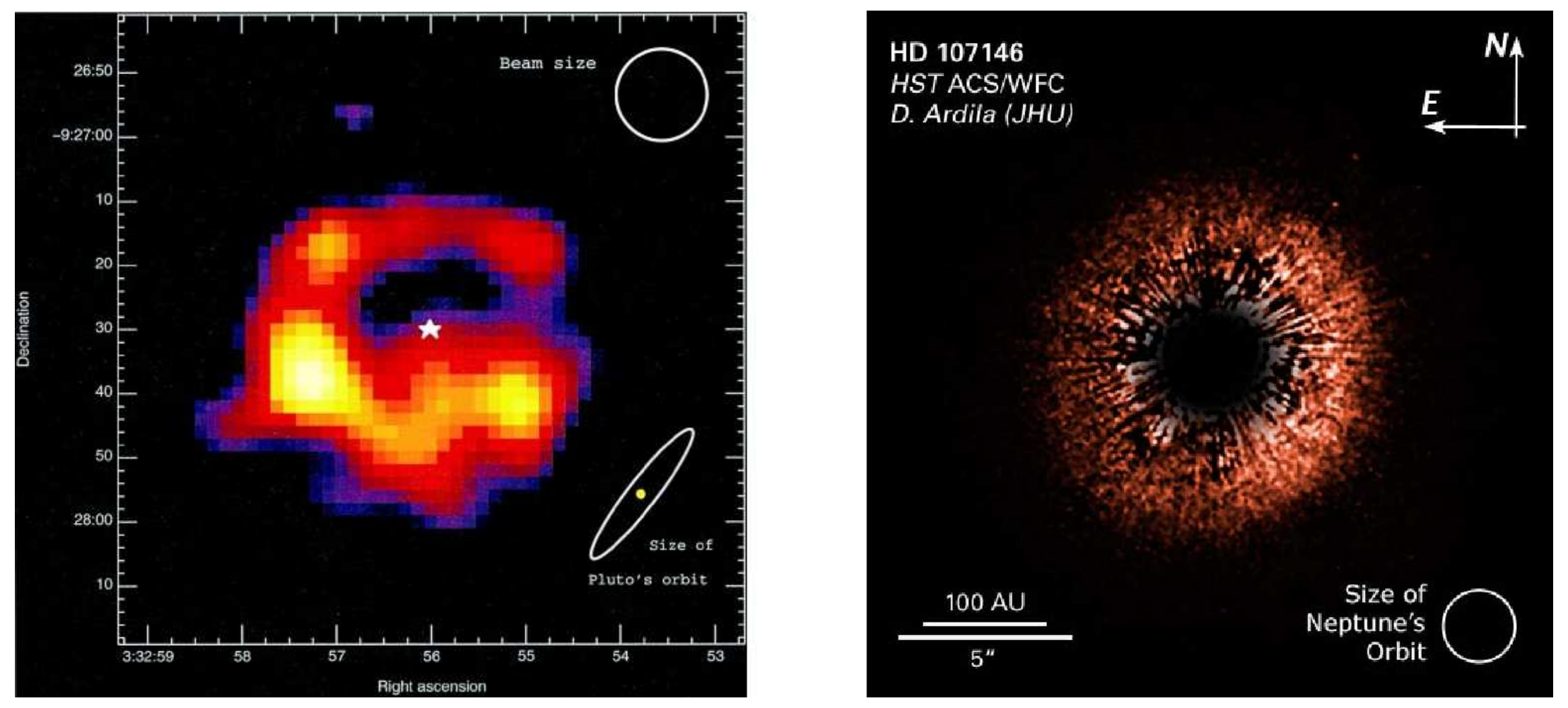

Figure 1: Left - ϵ Eridani in the sub-mm (Greaves *et al.* 1998), and HD107146 at optical (Ardila *et al.* 2004)

Models

Synthetic images of dusty planetary systems are readily computed using the dust–model described above. The following considers simple 1-planet systems, which are described by only 3 parameters: the planet's eccentricity e_p, the tilt of the disk midplane i from a face–on line of sight, and the light-scattering parameter g. To illustrate how the dust–disk's appearance depends on these parameters, we consider three simple cases:

- a planet having eccentricity $e_p = 0.6$ embedded in a face–on ($i = 0$) dust–disk composed of symmetric light–scatterers having $g = 0$. See Figs. 2–3.
- a planetless disk that is tilted by $i = 30°$ and composed of forward–scattering grains having $g = 0.6$. See Fig. 4.
- a combination of the above: $e_p = 0.6$, $i = 30°$, and $g = 0.6$. See Fig. 5.

Results are displayed in pairs of figures: contour's of the disk's 'apparent' optical depth = unprojected optical depth × phase function $\Psi(\phi)$, and radial profiles of the optical depth.

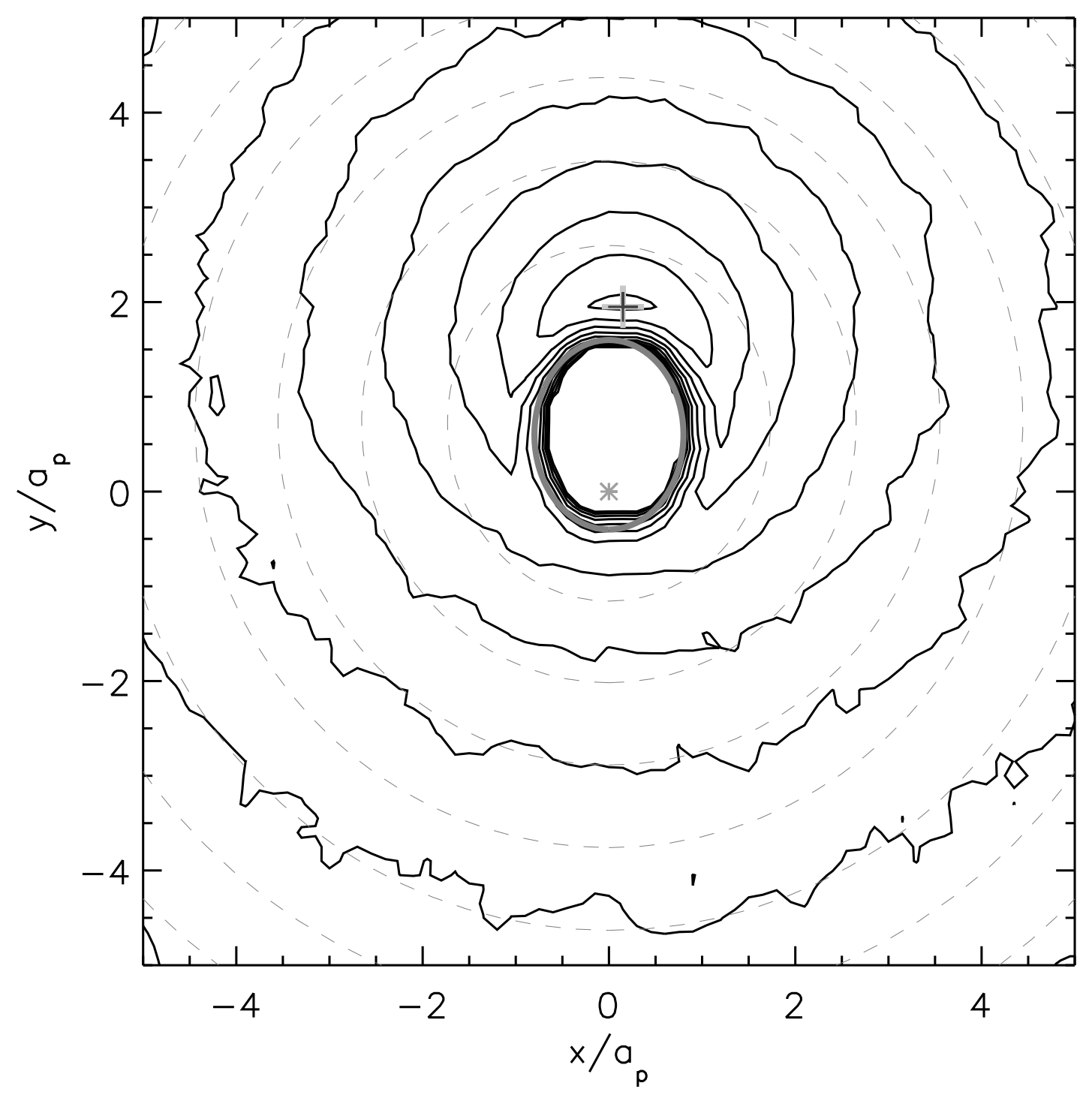

Figure 2: Dust disk perturbed by a planet with $e_p = 0.6$ with periapse oriented downward, while embedded in a face–on ($i = 0$) disk of symmetric light scatterers ($g = 0$). Solid curves are optical depth contours, with dashed curves indicating dust streamlines that are forced by the planet.

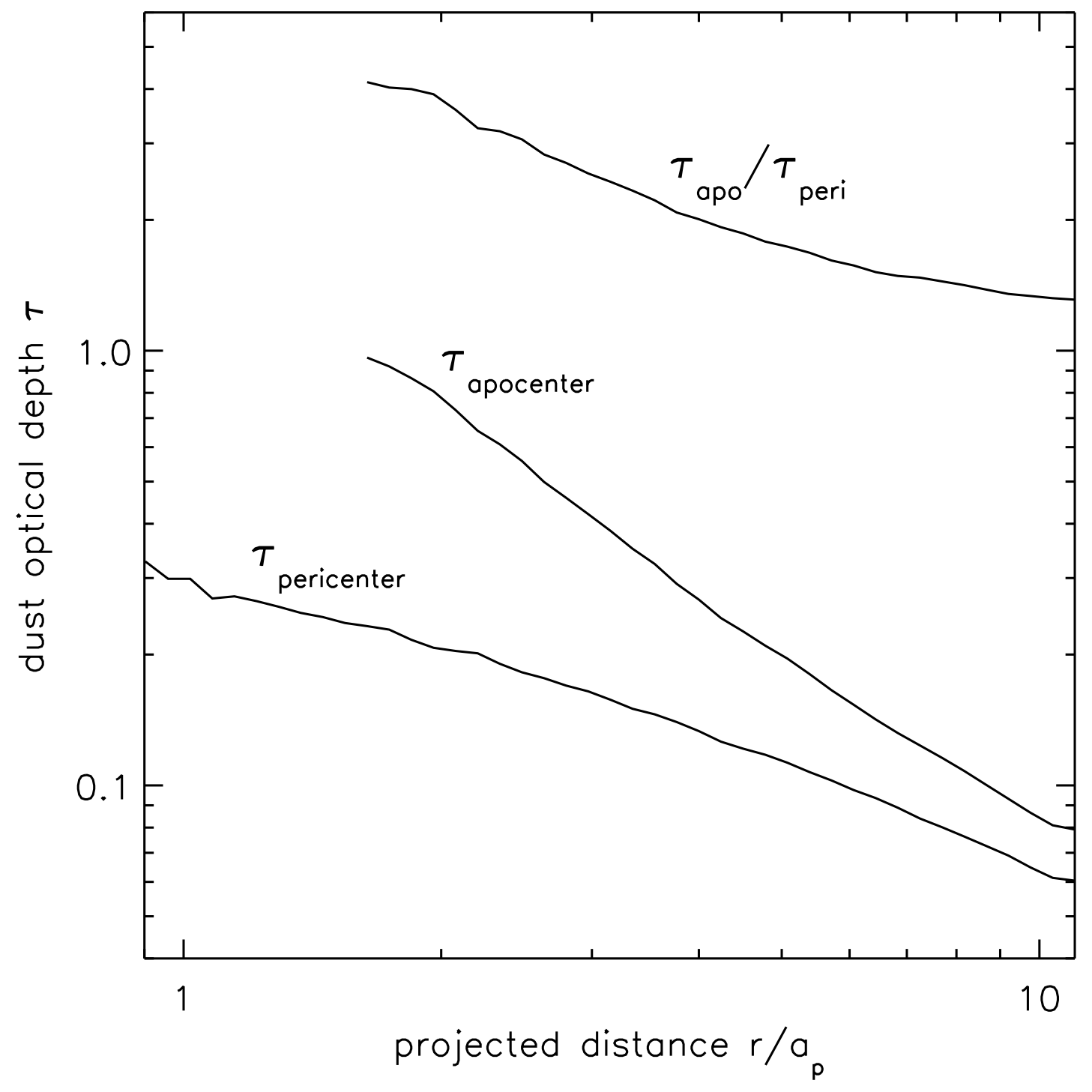

Figure 3: Optical depth profiles of the face–on disk of Fig. 2 along the direction of the planet's apocenter and pericenter, and their ratio.

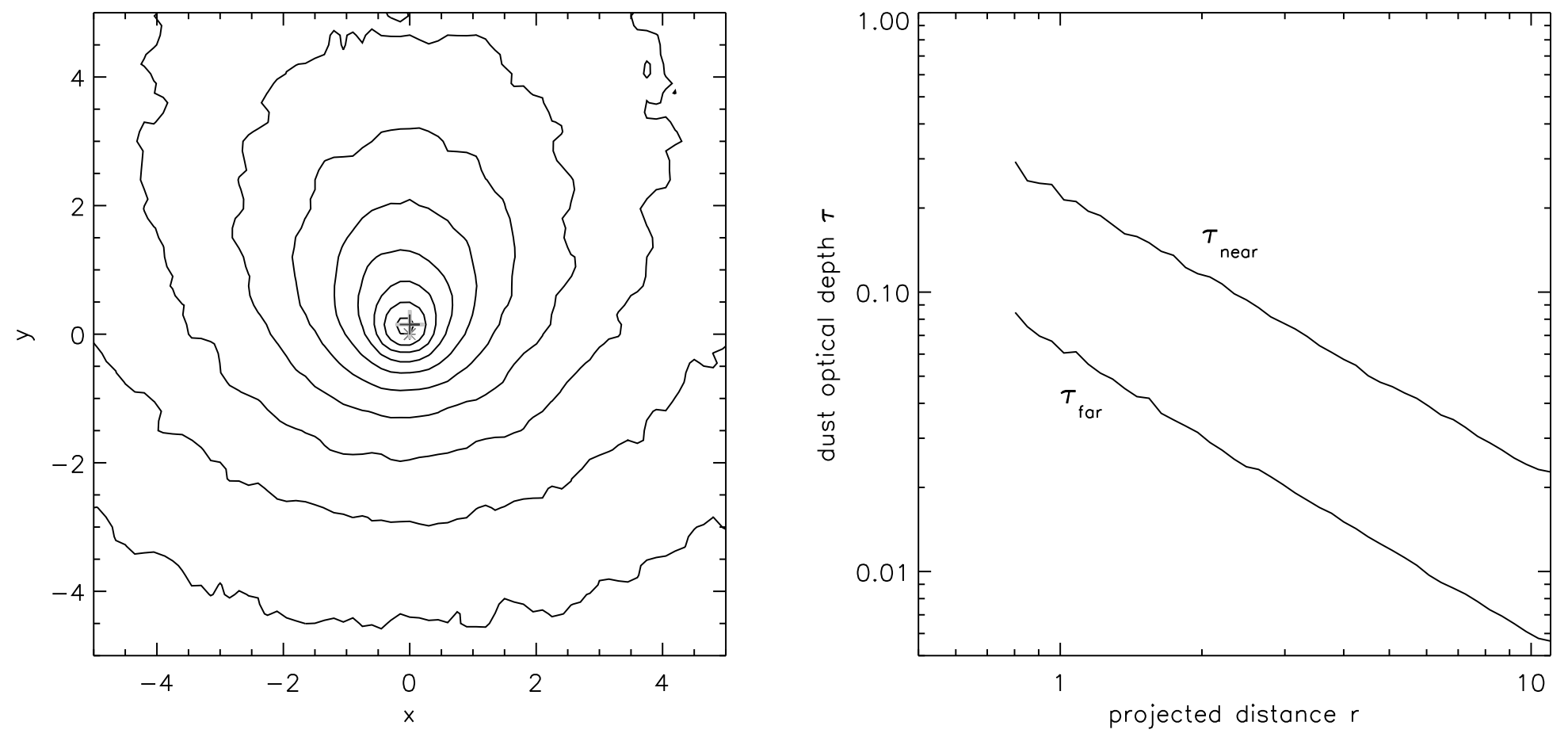

Figure 4: Left—contours of the disk's 'apparent' optical depth for a planetless disk inclined by $i = 30°$ from the line of sight. Forward scattering ($g = 0.6$) causes the disk's nearer/upper edge seem brighter. Right—apparent optical depth profiles along the near (upwards) and far (down) edges of the disk.

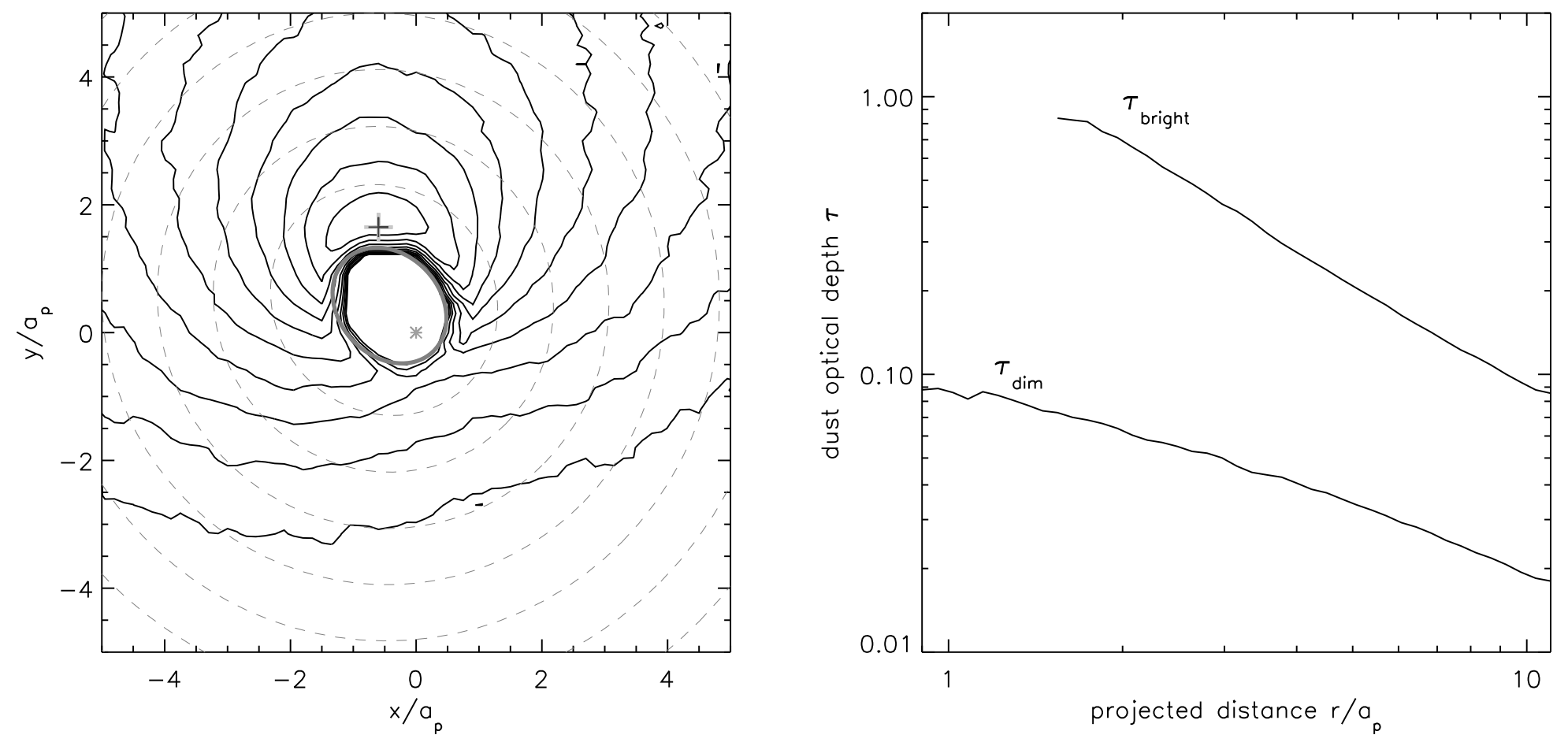

Figure 5: Apparent optical depths and streamlines in a tilted ($i = 30°$), forward scattering $g = 0.6$ disk containing a planet $e_p = 0.6$ whose periapse is $45°$ away from the disk's ascending node.

Findings and Future Activities

Both planetary perturbations and asymmetric light scattering may be contributing to the asymmetries seen in dusty circumstellar disks. Fig. 2 shows that planetary perturbations tend to steepen a disk's optical depth along the direction of periapse, with the opposite true along apoapse. Likewise, forward scattering in a tilted disk makes the nearer edge appear brighter (Fig. 4). However this disk's apparent optical depth profiles exhibit the same radial dependence, which is distinct from a disk disturbed by a planet (Fig. 2). Thus we are optimistic that one can disentangle these two effects—forward scattering versus planetary perturbations—in a more general system like that of Fig. 5.

Our next activity will be to employ a dusty multi–planet model in an effort to diagnose the faint warp seen in the β Pictoris disk (see Fig. 6).

Figure 6: 400×100 AU of β Pictoris seen edge–on at optical wavelengths (Heap *et al.* 2000). The solid black line is the mid-plane of the disk far the star, and the dotted line inclined at $2.5°$ indicates the tilted inner $r \lesssim 100$ AU disk's mid-plane.