A Search for Planet Signatures in the Innermost Parts of Protoplanetary Disks with Long Baseline Interferometry

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Long baseline interferometry represents a primary way to investigate structures and sub-structures of protoplanetary disks down to milliarcsecond scales. This technique is not only suitable for determining the physical and geometrical properties of protoplanetary disks, but also for searching for planets in the innermost regions of the protoplanetary disk. A planet in the inner-disk region clears out a gap in the circumstellar material, and this gap has a clear signature on the interferometric visibility and closure phases, as well as on the spectral energy distribution of the system. The CHARA Array interferometer, operating with baselines as large as 330 meters, has proved its ability of characterizing circumstellar disks, such as disks around YSOs and Be stars, and has the potential of finding gaps in the innermost parts of protoplanetary disks trigged by planets. The output of CHARA observations ultimately will help us understand the process of planetary formation and evolution.

Introduction

One key to understanding planetary formation lies in the study of protoplanetary disks of young stars and their structures, which provides the initial conditions for the development of planets. Recent simulations of planetary formation theory suggest that if present, a planet in the innermost regions of a protoplanetary disk clears out a gap in the circumstellar materials indicating that the inner disk has evolved while the outer disk has not. It is thus necessary to shed light on the role of gaps in these disks as part of the disk-planet interactions in the various planet migration scenarios.

To date, the presence of gaps has mainly been revealed by spectrophotometry though the deficit that a gap produces in the SEDs of protoplanetary disks (Brown et al. 2007, Forrest et al. 2004, Calvet et al. 2002), which makes it difficult to fully characterize these disks.

Long baseline interferometry represents a primary way to investigate the disks' structures and sub-structures down to the milliarsec scale. This method is very promising since a planetary gap has a clear signature on the interferometric visibility and closure phases. Early YSO and Be star disk studies using interferometry are demonstrated in Monnier et al. 2006, Kraus et al. 2010, Gies et al. 2007, and Schaefer et al. 2010.

The CHARA Array

The CHARA Array is an optical/near-infrared interferometric array located on Mount Wilson, CA, and operated by Georgia State University. CHARA consists of six 1-meter alt-az telescopes with15 non-redundant baselines ranging from 34 to 331 m (see Fig. 1). The current resolution of CHARA is about 0.6 mas in the K'-band and 0.4 mas in the V band, and the current limiting magnitudes for the Array are K~8.5 and V~12.

With its unprecedented angular resolution, CHARA is able to provide important new insights on the science of YSOs as demonstrated in recent published studies on AB Aur and MWC 275 (Tannirkulam et al. 2008a, b).

Figure 1

Modeling

Simultions of disks perturbed by embedded bodies 0.1 – 2 M_J (Jupiter masses) at distances of 1-10 AU from the star show that the most common result is the opening of a tidally produced gap (Lin & Papaloizou 1993). These simulations show that observable perturbations due to the scattered light by the disk wall at the outer edge of the gap are best shown in the visible to the mid-infrared and that they roughly scale with planet mass and orbital distance (Jang-Condell 2009).

In order to demonstrate the effect of the presence of a gap in a circumstellar disk on the interferometric signal, we present here a simple 2-D radiative transfer model of a gas-rich inner part of a circumstellar disk. We assume the geometry of an axi-symmetrical disk where the density distribution function is given by:

$$\begin{cases} \rho(\mathrm{r},\mathrm{z}) = 0\ ,\ r < r_0 \\ \rho(\mathrm{r},\mathrm{z}) = \rho_0 (r/r_o)^{-n} \exp(-1/2(z/h)\hat{}2),\ r > r_0 \end{cases}$$

where $\rho_0$is the base density at the stellar equator, r_s is the outer radius of the gap, and h(r) is the scale height along the vertical axis. We assume that the particle opacity is a power law in frequency, and that the temperature profile in the disk to be a function of the radial distance from the star:

$$T(r) = T_0 (r/r_0)^{-q}$$

where T_0 is the disk temperature at the inner edge, is assumed to be equal to 0.6 of the stellar effective temperature. The model generates infrared images of a central star surrounded by a truncated disk, computes fast Fourier transforms of the images, and predicts the interferometric observables that are directly comparable to the data. Figures 2 and 3 show intensity maps of different gap sizes in the disk that could be created by different planet masses, and their corresponding visibility curves.

Gap Opening

Figure 2

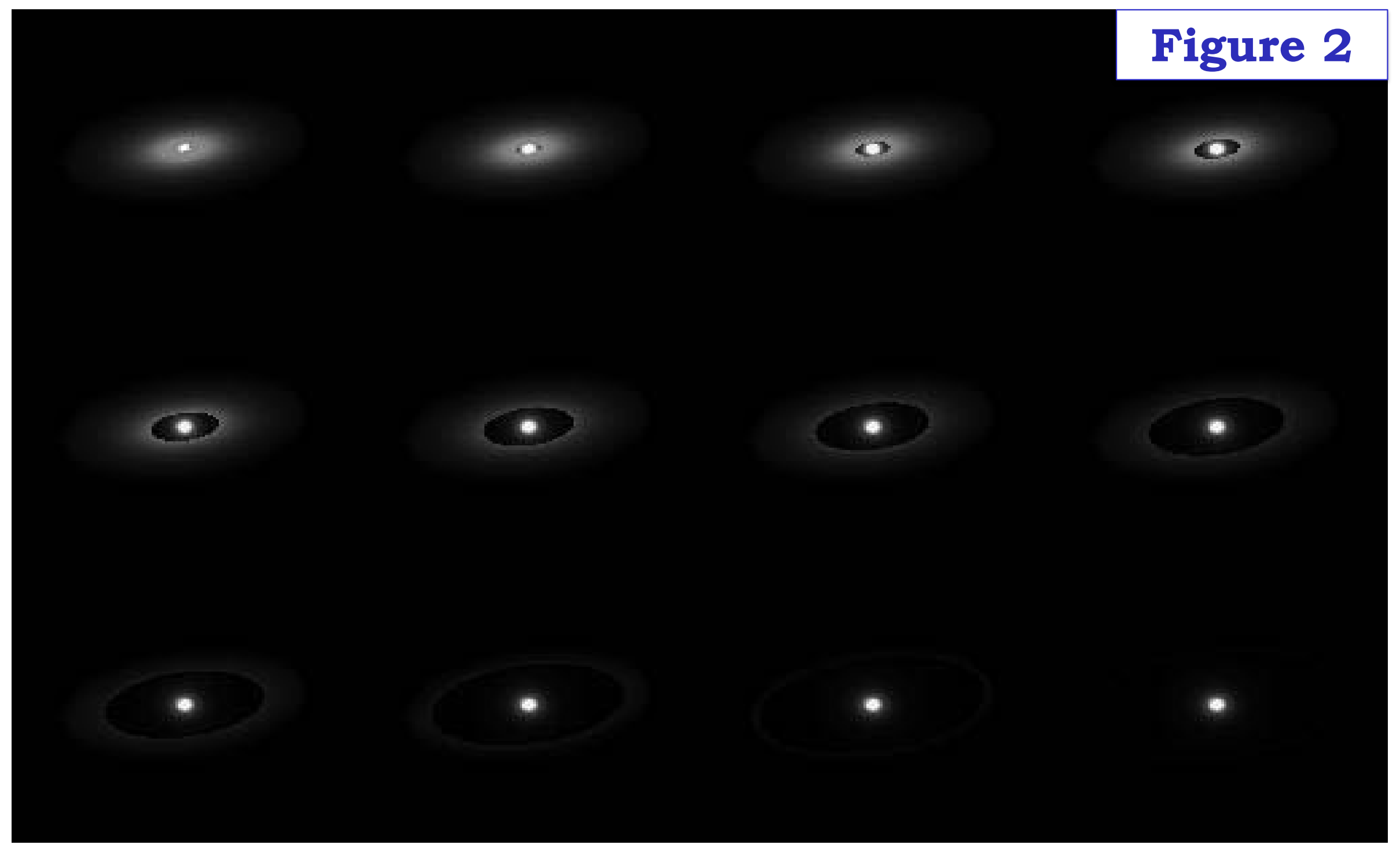
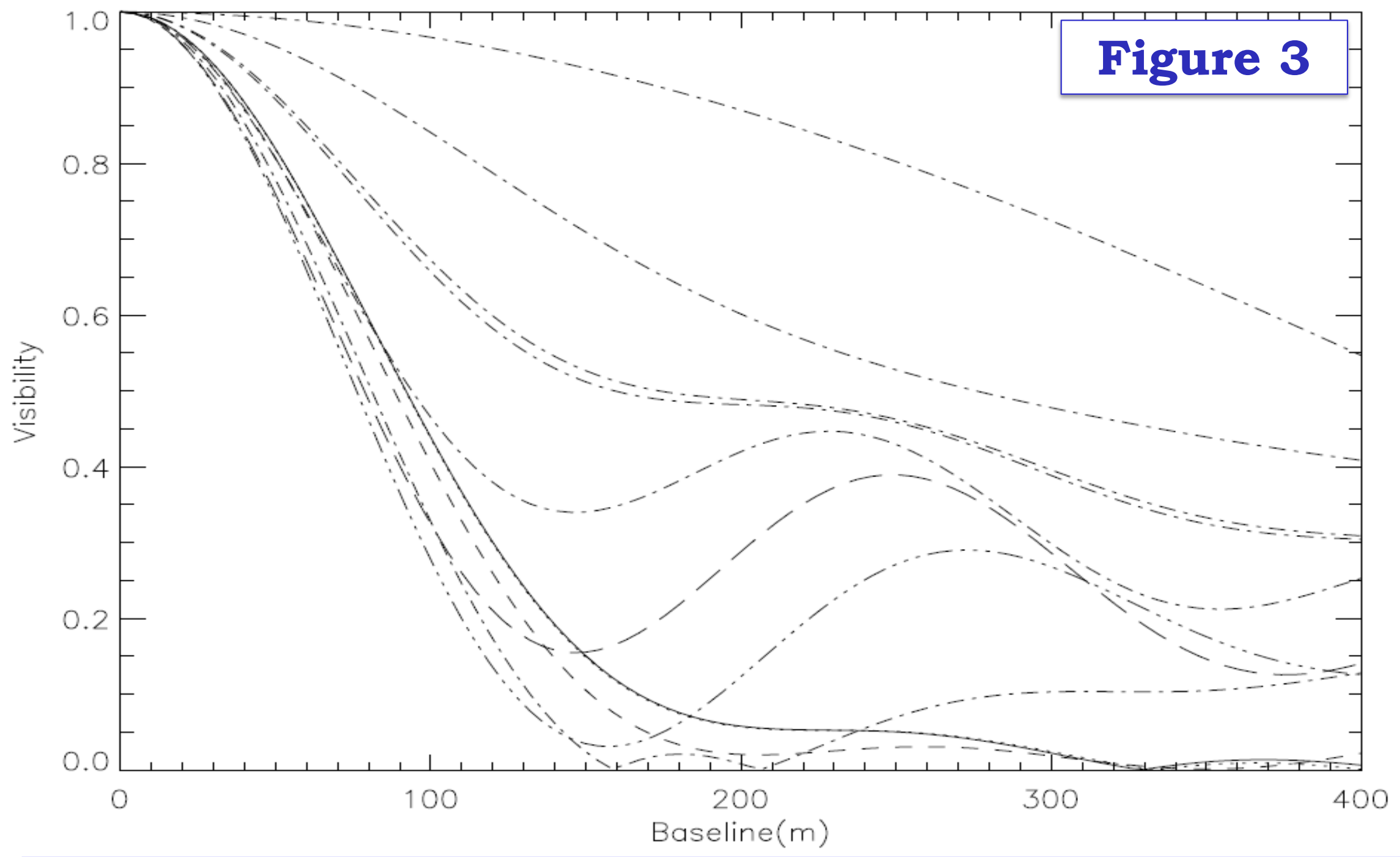


Figure 3



More detailed physical models of disk-planet interactions and the formation of gaps in protoplanetary disks exist in the litterature (e.g. Brown et al. 2009, Jang-Condell 2009, Varniere et al. 2006, Lubow et al. 2006). As an example, we show simulation results from Varniere et al. (2006) in the left and middle panels of Figure 4, which present the scattered light images produced from Monte Carlo simulations assuming a central star of 1 solar-mass and 2.5 solar-radii, and an effective temperature of 4 kK without and with a 2M_J planet located at 1 AU (Varniere et al 2006). The width of the resulting gap due to the presence of the planet is 1 AU. These simulations show that surface brightness of the outer gap edge is about 4 times larger than the emission from the smooth disk at the same location due to the direct illumination of the outer wall of the gap, which makes it easily detectable with long baseline interferometry at CHARA.

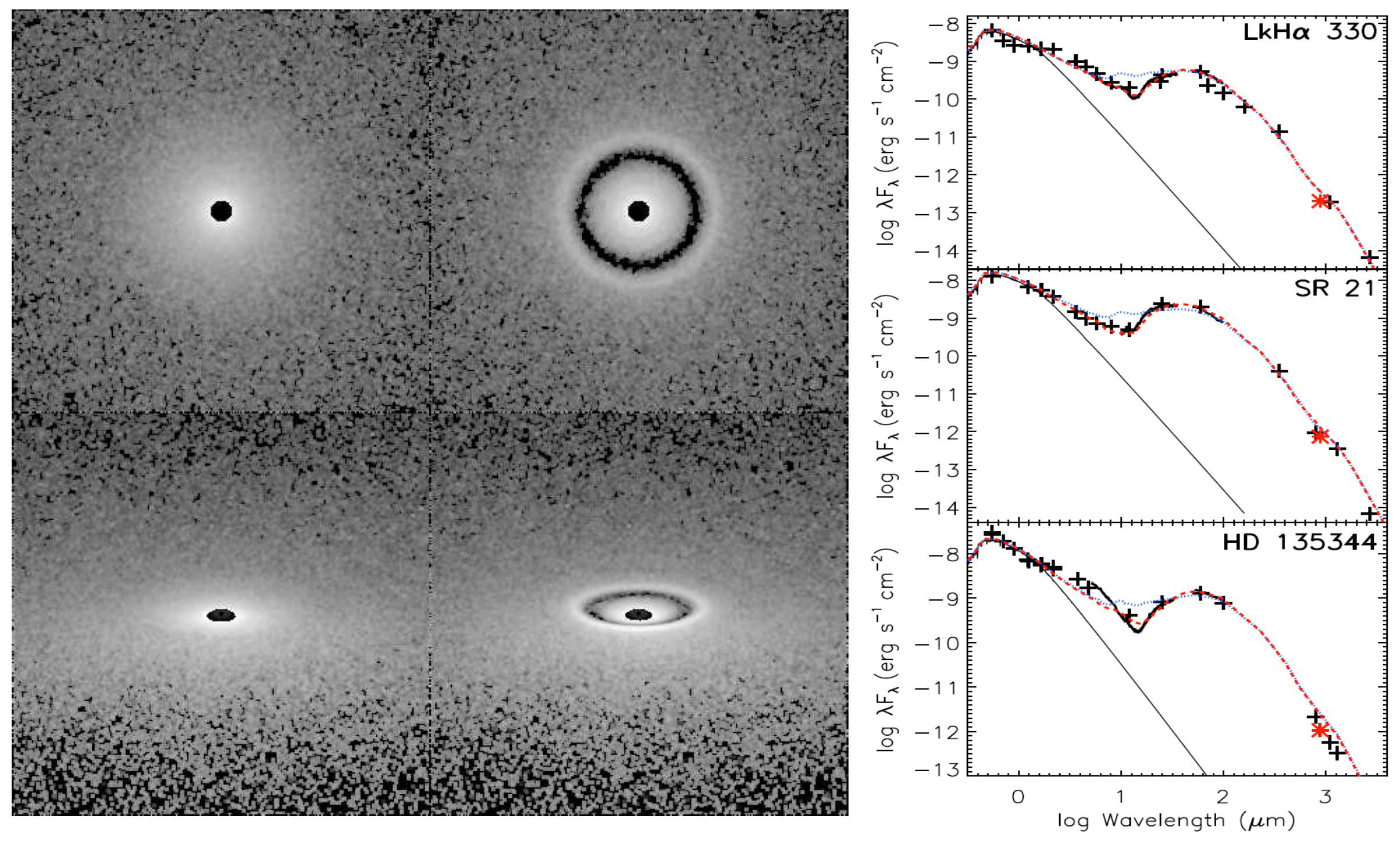
Planet Mass

To open a gap, a planet must be massive enough (> 0.1 M_J) so that the spiral density waves dissipated in the disk could overcome the inward flow that is due to the disk viscosity (Matsumura et al. 2005). Simulations show that the gap-opening mass depends on the disk geometry, which can be determined via long baseline interferometry:

$$\frac{M_{Planet}}{M_{Star}} \geq 6.324 \left(\frac{h}{a}\right)^{5/2}$$

where h is the local scale height of the protoplanetary disk and a is the orbital radius of the planet (Matsumura et al. 2005, Rafikov et al.2002).

Figure 4



Conclusion

We propose to establish the most accurate and extensive set of observational constraints on planetary gaps in the innermost parts of circumstellar disks of young stars and stellar objects using the CHARA Array interferometer. Current instruments can only detect planetary gaps in the outer regions of the disks because of the insufficient angular resolution. The indirect gap detection through its impact on the SED is untrusted since the presence of a gap produces small changes to the overall SED of the system, which makes it difficult to confirm a gap detection. With this program, we would like to make the first step towards the search of planet signatures in these systems using CHARA's high angular resolution and multi-wavelength capabilities.

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