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Pericentre Glow: A Signature of Hidden Planets in HR 4796?

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Abstract. Mid-IR observations of the disc of dust around the main sequence A0 star HR 4796A show an asymmetry which may be indicative of gravitational perturbations from an unseen planetary system. This paper describes the *pericentre glow* mechanism by which a planetary system could be causing the observed asymmetry and discusses the implications of the observations for the existence of planets hiding in the HR 4796 disc.

1. Introduction

The disc of dust around the A0V star HR 4796A provides an important opportunity for studying the planetary formation process, since the system's age, ~ 10 Myr, places it at an evolutionary epoch when any planetary system should be substantially formed. The mid-IR and near-IR emission from this disc has been shown to be concentrated in two lobes, one either side of the star (Schneider et al. 1999; Telesco et al. 2000). This indicates that the disc is being observed nearly edge-on, and that its inner region, ~ 40 AU in radius from the star, is almost completely devoid of dust. Like the dust discs found around the main sequence stars β Pictoris, Fomalhaut and Vega, its optical depth implies that the collisional lifetime of the 1-100 μm-sized dust that is seen is much shorter than the age of the system, implying that this dust must be continually replenished (Backman & Paresce 1993). The most likely source of dust in HR 4796 is collisions between a population of larger bodies which, like the objects in the Kuiper belt in the solar system, formed due to the aggregation of interstellar dust grains in the protoplanetary nebula, but which did not manage to grow to sufficient size to develop into a planet. This picture is supported by the existence of the solar system-sized central cavity which implies that, like the solar system, bodies that are large enough to be able to clear a cavity (i.e., planets) were able to form there. However, the existence of such planets is, as yet, purely speculative.

It is known from observations of the disc of dust in the solar system, the zodiacal cloud, that the gravitational perturbations of a planetary system to the orbits of particles in a debris disc can cause asymmetries in that disc's structure (Dermott et al. 1998). Such asymmetries may be present in the observed structure of the β Pictoris dust disc (Kalas & Jewitt 1995). Observations of the HR 4796 disk also show an interesting asymmetric feature (Telesco et al. 2000): the mid-IR lobes appear to be of unequal brightness. In a recent paper, Wyatt et al. (1999) modelled these observations and showed that such a lobe brightness asymmetry is to be expected if there is another body orbiting HR 4796A that is on an eccentric orbit, since the long-term effect of the gravitational perturbations from this body would force the centre of symmetry of the disc to be offset from the star in a direction away from the pericentre of the body's orbit, thus causing the dust near this forced pericentre to glow.

The dynamics behind the pericentre glow phenomenon is described in §2 and the pertinent results of the Wyatt et al. model are presented in §3. The implications of the model on the existence of planets hiding in the cavity region is discussed in §4.

2. Pericentre Glow

The long term gravitational perturbations from a planetary system to the orbits of any particles in that system are called secular perturbations (for a good review of the dynamics involved, see Murray & Dermott 1999). Their effect on a disc particle's orbit can be demonstrated using Fig. 1a. A particle on an orbit described by the eccentricity vector SD has an eccentricity, e, given by the length of the vector and a pericentre orientation (relative to an arbitrary direction), $\tilde{\omega}$, given by the angle that vector makes with the x-axis. The action of secular perturbations is to decompose the particle's eccentricity vector into forced (SC) and proper (CD) components. The forced component is that imposed on the particle's orbit by the planetary system, which is the same for all particles orbiting at the same distance from the star, and the proper component precesses anticlockwise about the forced component on a circle with a radius determined by the particle's intrinsic orbital properties.

Consider the break-up of one planetesimal in the disc, the orbit of which is described by the eccentricity vector SD in Fig. 1a. Initially, all collisional fragments have very similar orbits to the original planetesimal and so have eccentricity vectors that are almost coincident. The secular perturbations of any planets in the system then make these fragments' proper elements precess about the forced elements. However, since their orbits are slightly different, due to the velocity dispersion imparted in the collision, they precess at slightly different rates, which means that after a few precession timescales their eccentricity vectors are no longer coincident but randomly distributed about the dotted circle in Fig. 1a. There is evidence that such an evolution has occurred in the asteroid belt where there are families of asteroids the members of which orbit at the same distance from the Sun and which have eccentricity vectors spread around circles centered on the forced elements known to be imposed on their orbits by the solar system's secular perturbations; each family is thought to have been created by the break-up of a much larger asteroid. Fig. 1b shows the eccentricity vectors of the asteroids in the Eos, Themis, and Koronis asteroid families.

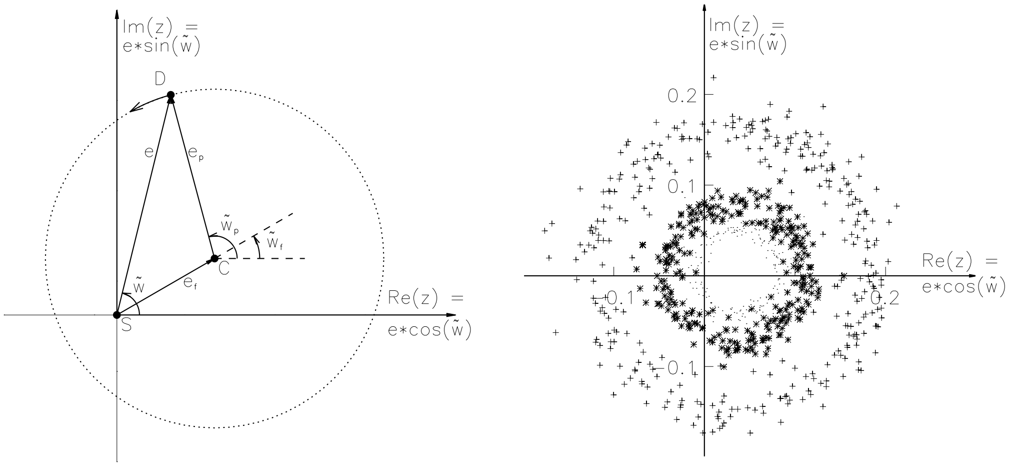

Figure 1. (**a**) The evolution of the eccentricity vector of a debris disc particle due to the secular perturbations from a planetary system (see text for discussion). (**b**) The eccentricity vectors of asteroids in the Themis (+), Eos (*) and Koronis (.) families.

It can be shown by considering the geometry of each of the orbits in the eccentricity vector distribution of Fig. 1b that the disc of material comprising one families' members forms a uniform torus that is rotationally symmetric not about the star, but about a point that is offset from the star in a direction away from the forced pericentre direction, $\tilde{\omega}_f$, by an amount that is proportional to the forced eccentricity imposed on the families' orbits, e_f (Wyatt et al. 1999). Since the offset direction, $\tilde{\omega}_f$, and amplitude, e_f, is the same for all families at the same distance from the star, a relatively narrow disc formed by the break-up of Kuiper belt-like objects should appear rotationally symmetric about a point offset from the star, the location of which is determined solely by the secular perturbations imposed on the disc by any planets in the system, which may themselves be unseen. Such an offset would cause material on the forced pericentre side of the disc to be closer to the star than that on the forced apocentre side, thus causing that material to be hotter, and therefore brighter, a phenomenon we call pericentre glow. This is the phenomenon that we think may be causing the HR 4796 disc's lobe brightness asymmetry.

3. The HR 4796 Disc Model

It was the aim of the modelling to see whether the pericentre glow phenomenon could indeed be responsible for the brightness asymmetry, and if so, to find how large a forced eccentricity, e_f, (and hence an offset) would have to have been imposed on the disc to be causing the observed 5% asymmetry. The essence of the modelling is a program called SIMUL which was developed by Stan Dermott and his Solar System Dynamics group at the University of Florida for the study of the detailed observed structure of the zodiacal cloud. This program creates a three-dimensional model of the distribution of dust in a system given the

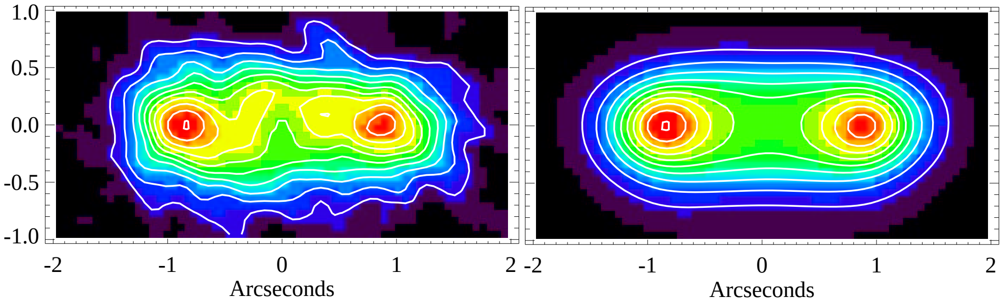

Figure 2. 18 μm images of the HR 4796 disc: the Telesco et al. (2000) observation (left), and the Wyatt et al. (1999) model of this observation (right). The contours in both of these images are linearly spaced at 58, 93, 128, 163, 198, 234, 304, 339, and 374 mJy/arcsec^2.

distribution of the orbital elements of the constituent particles, thus providing a unique way of linking a disc's observed structure with the physical and dynamical evolution of its constituent particles.

The distribution of orbital elements of the dust particles in the HR 4796 disc model was taken from a combination of our understanding of the consequences of secular perturbations (e.g., the distribution of their eccentricity vectors was assumed to be circularly symmetric about a forced eccentricity similar to Fig. 1b), and inferences from the observations (e.g., the distribution of their semimajor axes was assumed to follow a power law between inner and outer bounds). The details of the model can be found in Wyatt et al. (1999); it is only the asymmetry that will be discussed here. It was found that having a forced eccentricity imposed on the disc does indeed cause the disc to have an offset centre of symmetry, and that this could cause the disc's lobes to appear to have asymmetric brightnesses. The forced eccentricity that was needed in the model to cause the 5% asymmetry was found to depend on the orientation of the forced pericentre to the line of sight; for the majority of the possible forced pericentre orientations, it was found that the observations could be matched with a forced eccentricity of 0.02, while for the remaining orientations a higher forced eccentricity was needed. The Telesco et al. observation and the final Wyatt et al. model of that observation (which has $e_f = 0.02$) are shown in Fig. 2. This figure shows that as well as fitting the asymmetrical heights of the lobes, the model also gives an extremely good fit to the lobes' horizontal and vertical structure.

4. ... Hidden Planets in HR 4796?

What can we conclude from the modelling about whether there are any planets hiding in the HR 4796 disc? What the modelling explicitly shows is that if $e_f = 0.02$ is imposed on the particles in the disc's lobes at $a \approx 62$ AU, then, depending on the orientation of the disc to our line of sight, a 5% asymmetry could be observed. However, it does not specify the origin of e_f, which could come from one or more massive perturbers either interior or exterior to the disc.

If we assume that there is a planetary system inside the disc cavity that is causing the hole, then it would be the outermost planet of that system that affects the outer disc most. By analogy with the Kuiper belt, the inner edge of which is at the 2:3 resonance with Neptune, the orbit of this outermost planet could have $a_{pl} = 62 * (2/3)^{2/3} = 47$ AU. This means that to cause $e_f = 0.02$ at 62 AU its orbit only needs to have $e_{pl} > 0.023$. Furthermore, assuming that the timescale for this asymmetry is the same as the secular precession timescale, which is inversely proportional to the mass of the perturbing planet, then the age of the system implies that this planet need only have a mass of $> 10M_\oplus$ to be causing the asymmetry. This leads to the conclusion that if any planets did form in the disc, then unless they were born with a negligible eccentricity (which could, e.g., be possible due to the interaction of the planet with a massive disc, Ward & Hahn 1998), or an adverse observing geometry prevents it, the lobes would inevitably have asymmetric brightnesses.

In this system, however, we may not need to invoke hidden planets to explain the forced eccentricity in the lobes, because there is another perturber in the system, the binary companion HR 4796B. The orbit of this binary is unknown. Observations in 1931 put the projected separation and position angle of the two stars at [$6\farcs9$, 226°], while observations in 1992 put them at [$7\farcs7$, 225°] (Jura et al. 1993). If both of these observations were absolute, then the two stars cannot be bound, since it can be shown that for bound orbits, the motion of the star on the sky in $''$/yr:

$$v_{obs} < 2\pi\sqrt{2(M_A + M_B)/\rho'' d^3}, \tag{1}$$

where $M_A + M_B \approx 2.56$ is the total mass of the binary pair in solar masses, $d = 67.1$ is the distance to the stars in pc, and ρ'' is the observed projected separation in $''$; i.e., the change in 61 years should have been less than $0\farcs6$. The most likely reason for the discrepancy is observational error and the two stars are bound; however, a preliminary search through archival observations was unable to determine whether this is indeed the case. If, for pedagogical reasons, we assume that the semimajor axis of the orbit is equal to its most statistically likely value[1] of $a_B = 697$ AU, then the orbit needs an eccentricity of $e_B > 0.18$ for the binary to be causing the asymmetry. Such a high eccentricity is to be expected for a binary this wide (Duquennoy & Mayor 1991) and would be consistent with a high apparent motion on the sky. In other words, the lobe asymmetry is also likely to be an inevitable consequence of the presence of the binary companion. Thus it appears that it would have been rather surprising if an asymmetry had not been observed in this disc!

It is most likely that both HR 4796B and the outermost planet of a planetary system are perturbing the disc. In this case it is difficult to make any quantitative statements about such a planet without first determining the orbit of HR 4796B. However, we do know that if the planet is very massive (e.g., $> 0.1M_J$, where $M_J = 10^{-3}M_\odot$ is the mass of Jupiter), then the magnitude and orientation of the asymmetry will be determined by the orbit of the planet, while it will be determined by the orbit of HR 4796B if the planet is much smaller than this. We also know that if the two perturbers have different orbital planes, and the mass of the planet were $\sim 0.1M_J$, then the disc could appear warped (Wyatt

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[1] $\log a'' = \log \rho'' + 0.13$, Duquennoy & Mayor 1991

et al. 1999). Clearly, if the orbit of HR 4796B was known, we would be able to determine its effect on the disc, and we would be able to set some quantitative constraints on any planets in the system; a detailed study that determines the orbit of HR 4796B is therefore warranted.

Of course, the asymmetry may not be a consequence of pericentre glow. Without detouring from the planetary theme, we can think of at least one mechanism for forming such an asymmetry: Many of the particles in the disc could be trapped in the 2:3 resonance of the outermost planet in the system, just like many Kuiper belt objects are trapped in that of Neptune. This would give the disc clumpy structure that would follow the planet in its orbit. If the asymmetry is caused by such a clump that is currently residing in one of the lobes, then in half a planetary orbital period, ~ 100 years, the asymmetry will be reversed. It would not, however, take 100 years to ascertain whether this was the case or not; such moving structure could be detected with current technology in ~ 3 years, since this is the time it would take for a clump (which could be detected in the residuals of a high S/N observation once a smooth model has been subtracted) to move 1 pixel on the Telesco et al. image.

In conclusion, because of the existence of HR 4796B which could be causing the asymmetry, the fact that HR 4796 is a 10 Myr old debris disc with a hole about the size of the solar system remains the best evidence for planets in this system. However, the modelling has shown that the observed asymmetry could have been caused by the perturbations of a $10M_\oplus$ planet and has shown the observations that are necessary if we want to be able to use the disc observations to make any quantitative statements about the planetary system.

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