All About GG Tau A

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ABSTRACT

At this Fest in honor of Hans Zinnecker's lifelong interest in star formation and multiple systems, we show a potpourri of results from our recent paper on GG Tau A, one of the best known forming multiple star systems.

Introduction

The GG Tau system is one of the best studied forming hierarchical multiple star systems known (see e.g. Dutrey et al. 2014, Beust & Dutrey 2005, Guilloteau et al. 1999, and many other references). It is a hierarchical quintuple system with projected separation of ~1500 AU between its A and B components. The more massive A component is a hierarchical triple with a projected separation of ~35 AU between its Aa and Ab components, with the latter recently observed also to be a binary with separation of ~4AU (diFolco et al. 2014). Fits to the proper motion of the binary suggest an a=32AU orbit if the system is co-planar, and a 62AU orbit if the system is misaligned by ~20 degrees. The triple is surrounded by a torus, sharply bounded at inner/outer radial dimensions of ~180 AU and ~260 AU, as well as a low density disk extending outwards to ~800 AU. Here, we summarize results described in Nelson & Marzari 2016, in which we simulate a system based on this configuration, exploring the behavior of the system and its evolution.

Physical Model and Numerical Method

- We use the Smoothed Particle Hydrodynamics (SPH) code VINE (Wetzstein et al., 2009, Nelson et al. 2009), to simulate the evolution of a system similar to GG Tau A in two spatial dimensions, using a total of ~1.88 million particles. Approximately ~10000 and ~8000 are allocated to the primary and secondary disks respectively, the rest to the circumbinary.
- We include radiative cooling using the prescription originally described in Nelson et al. 2000, in which a vertical structure model is used to define a "photosphere" temperature at each point in each disk, which is then used to define a blackbody cooling rate there.
- We implement a similar model to define radiative heating from the two stars, from light impinging on the disk photosphere at each location.
- Gravitational forces from both stars and self gravity of the disk material are included.
- Accretion from the circumstellar disks onto the stars is permitted. The mass and momentum of any particle traveling closer than 0.3 AU from either star is added to that star and the SPH particle is removed from the simulation.

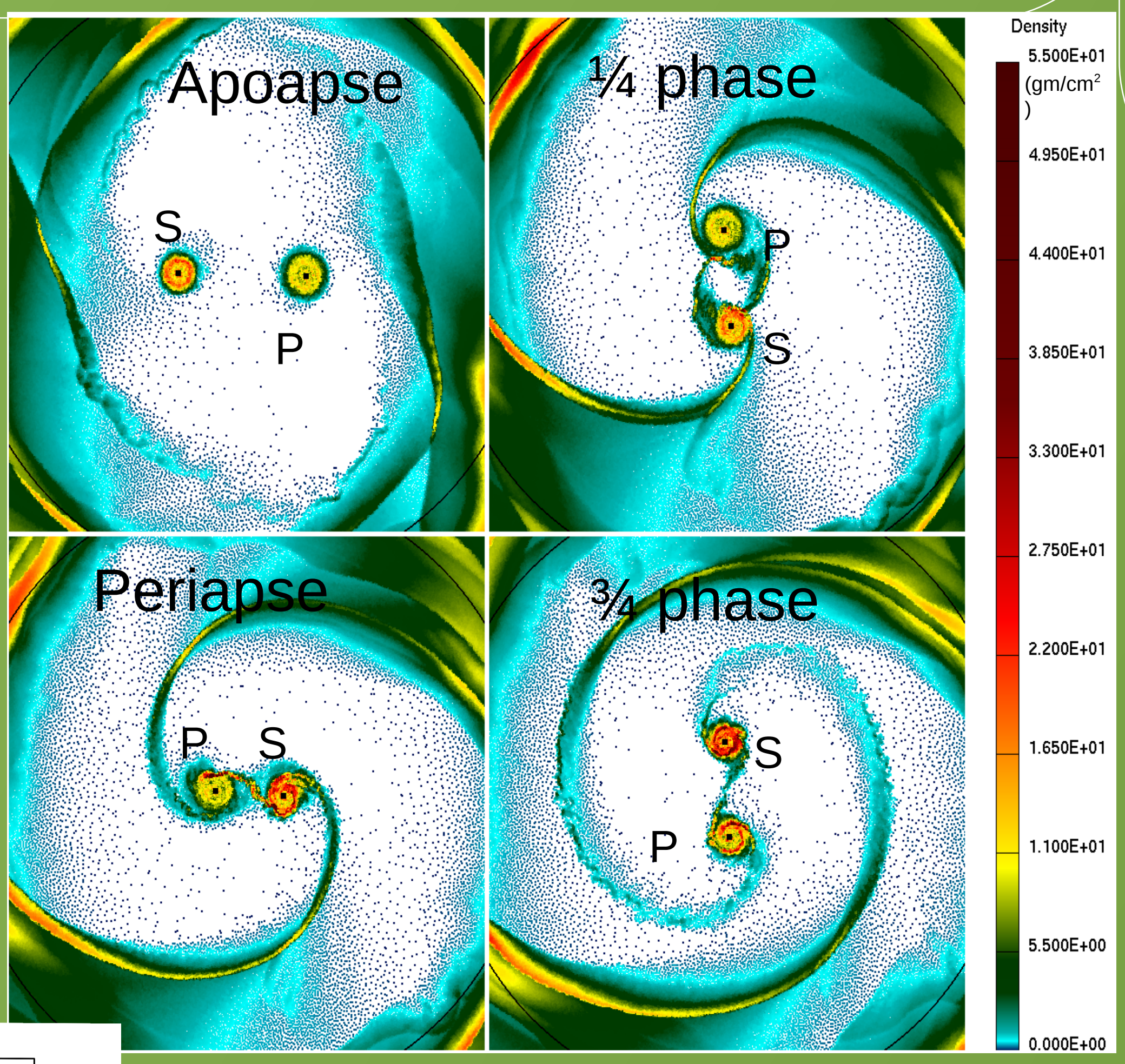


Figure 1: Snapshots of the circumstellar environment at intervals near t~3500yr, corresponding to the 8th orbit of the binary after the start of the simulation. **Large amplitude material streams develop during the orbit, strongest near periapse. A fraction of the material accretes onto the circumstellar disks and the rest returns to the torus. No streams of similar amplitude develop in models with a=32AU. Consistency with the observations of Pietu et al. (and others), which indicate such streams are present in GG Tau A, therefore favors an a~60~AU binary orbit.**

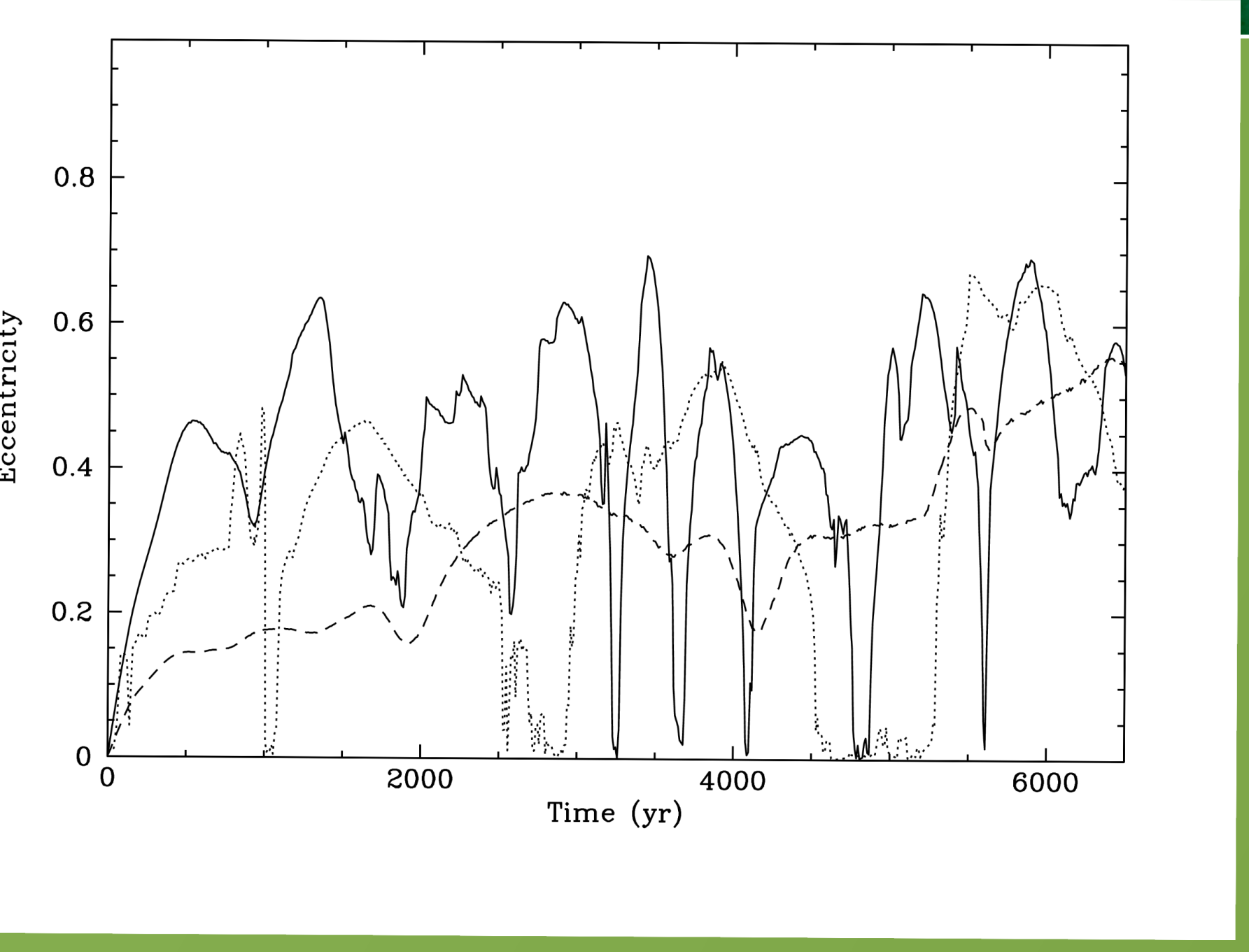


Figure 3: Eccentricity of the inner(solid), center (dotted) and outer edges (dashed) of the torus. The torus is eccentric in shape, with eccentricity varying to as high as e~0.6 . **If the GG Tau torus is similarly eccentric, then its inclination is incorrectly determined by deprojecting it into a circle. The *mutual* inclination of the torus and binary orbit is similarly ill-determined. Errors of ~20 degrees will occur for eccentricities seen here, consistent with the mutual inclination required in the family of proper motion fits (Köhler 2011) for GG Tau's orbit that favor a~60AU.**

Initial Conditions

We derive initial conditions from the observed parameters for the GG Tau A system as described in Guilloteau et al. 1999, neglecting the binarity of the Ab component discovered after the simulations were completed. Luminosities are as specified by Roddier et al. 1996. For the model presented here, we assume the following characteristics for the various components:

Stars

$M_P = 0.7M_{sun}$; $M_S = 0.6M_{sun}$; $L_P = 1.0L_{sun}$; $L_S = 0.76L_{sun}$

Orbital parameters a=62AU, e=0.3, initially at apoapse; T_{BIN} ~420yr

Circumstellar Disks: 0.5AU<r<10AU

Primary: $M_D = 0.001M_P$; Secondary: $M_D = 0.001M_S$

Surface Density: $\Sigma=\Sigma_0(1AU/r)^{-3/2}$; Initial Temperature: $T = T_0(R_0/r)^{0.9}$

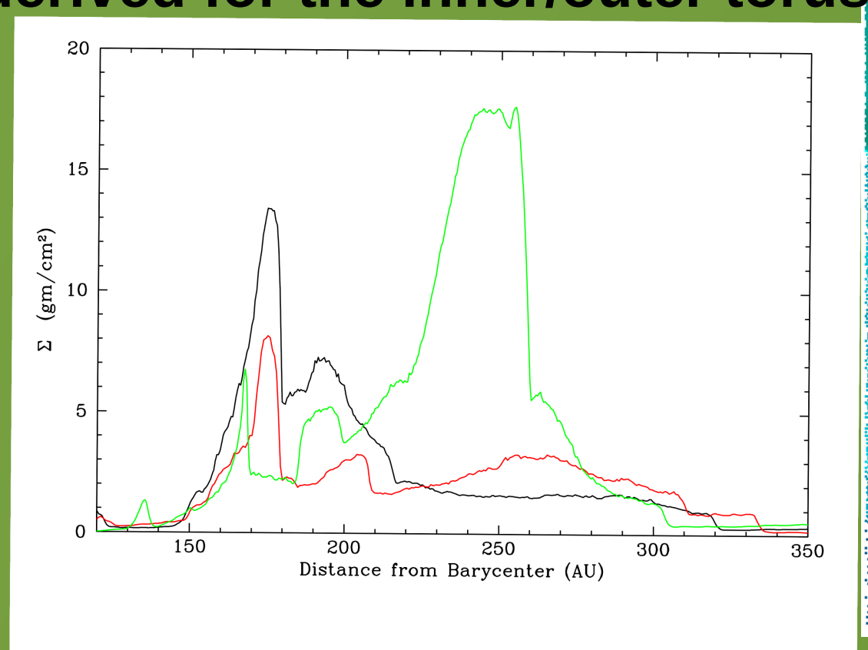
Circumbinary Material: Torus+Disk

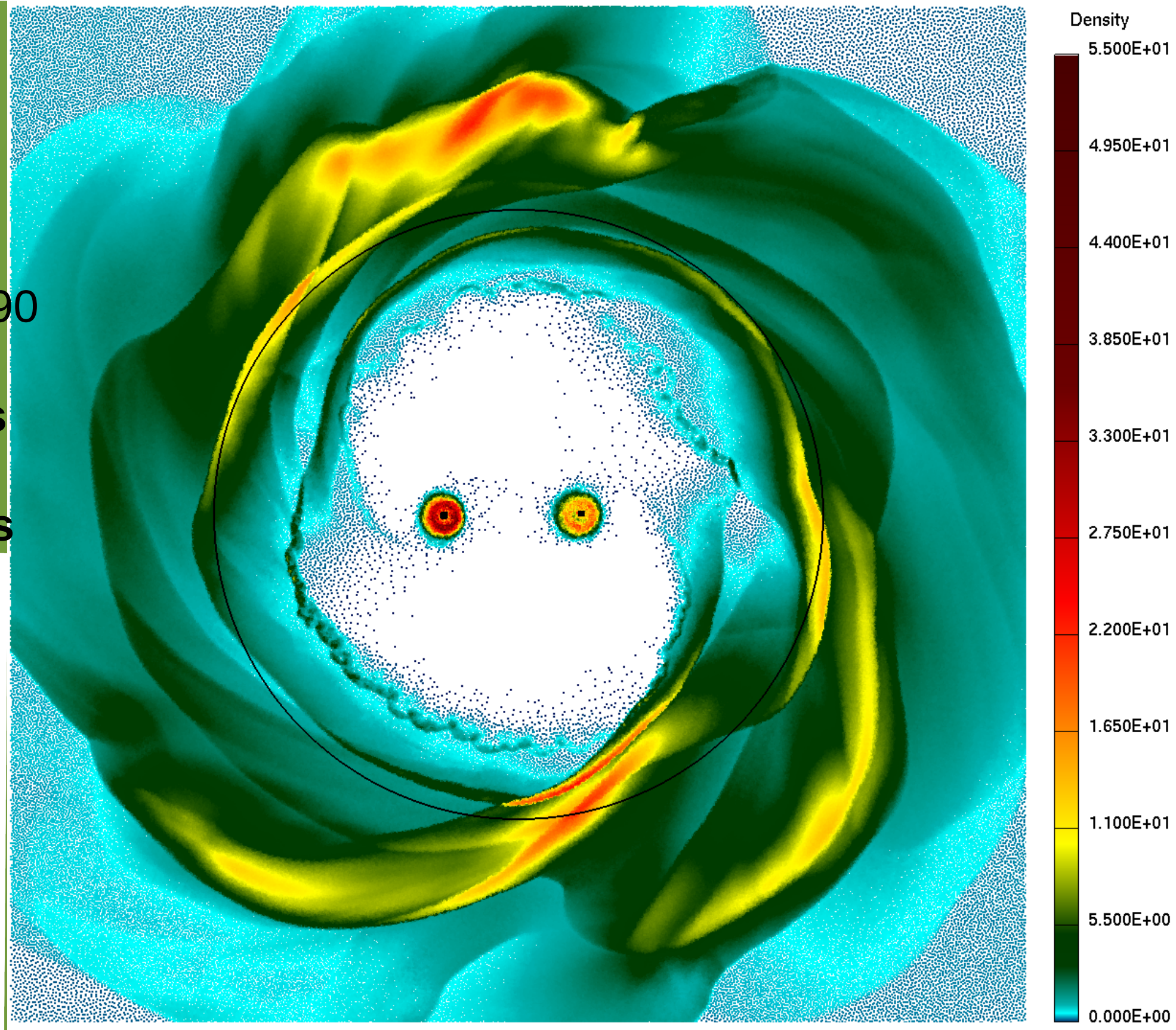
Mass: $M_{CB} = 0.1 (M_P + M_S)$

Torus (180-260AU. $M_T = 0.7M_{CB}$); Disk (180-800AU, $M_D = 0.3M_{CB}$)

Surface Density: Torus: Σ_T (const.); Disk: $\Sigma(r) = \Sigma_D (R_0/r^{-})^{1.5}$; Initial Temperature: $T =T_0(R_0/r)^{0.9}$

Figure 2: (a) Snapshot of the system at larger scale near t~5000yr, corresponding to apoapse of the 12th orbit of the binary after the start of the simulation. **Multiple, large amplitude and sharply defined spiral structures develop.** (b) Lineouts of the configuration in (a), taken at 0 (black), 45 (red) and 90 (green)degree projections from the origin. **Density transitions of factors of several, within distances of a few AU, are typical: consistent with the observed widths derived for the inner/outer torus boundaries.**





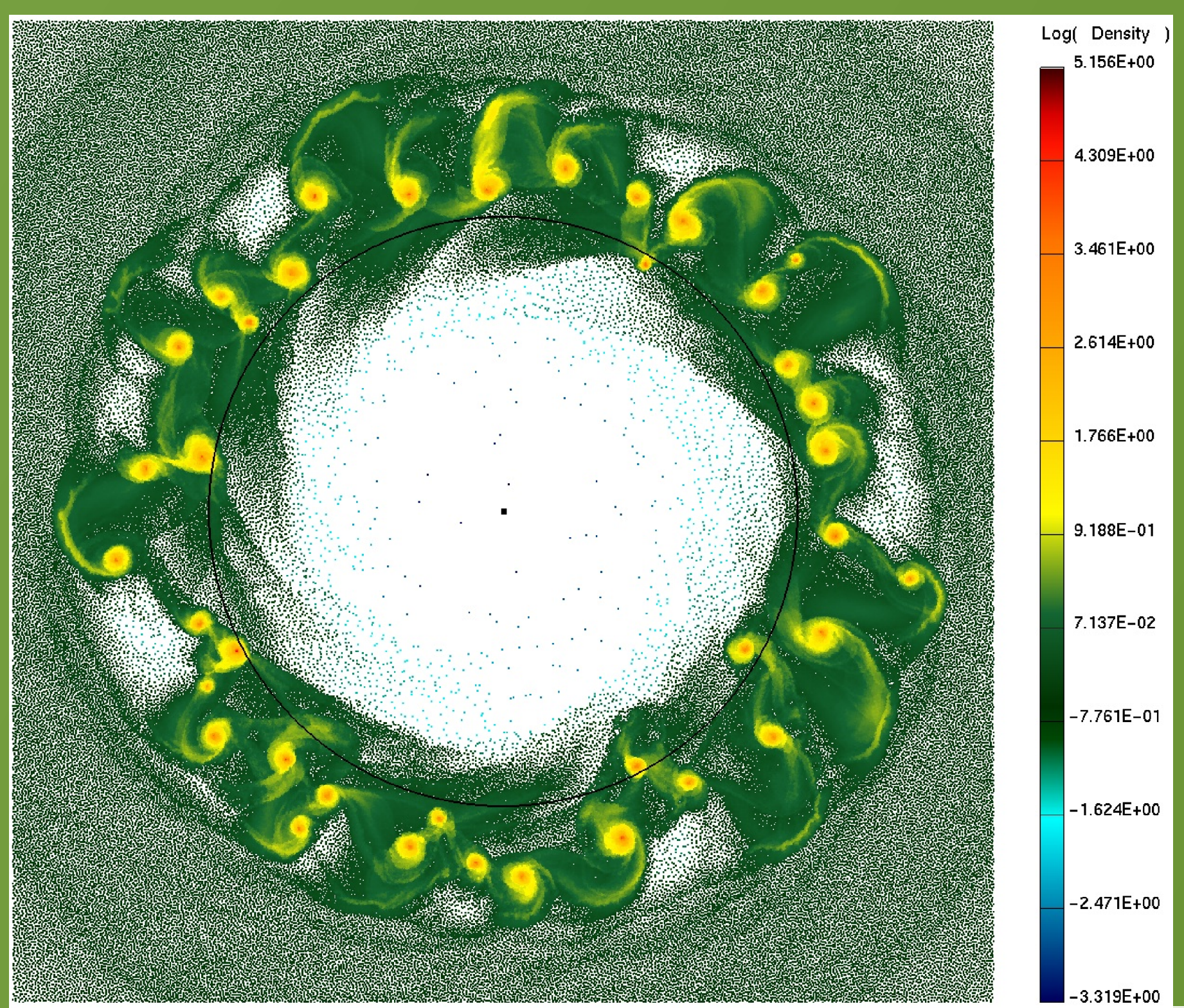


Figure 4: Substituting a single star of the same mass as the binary-thereby removing the binary torques as a heat source-causes the torus to fragment into ~40 objects within a single torus orbit. Similar behavior occurs if the stellar heating is removed. **We conclude from this *highly* unphysical outcome that the GG Tau torus is very near its stability limit and that both heating sources are critical to maintaining it against fragmentation. We speculate that it may fragment into additional components before**

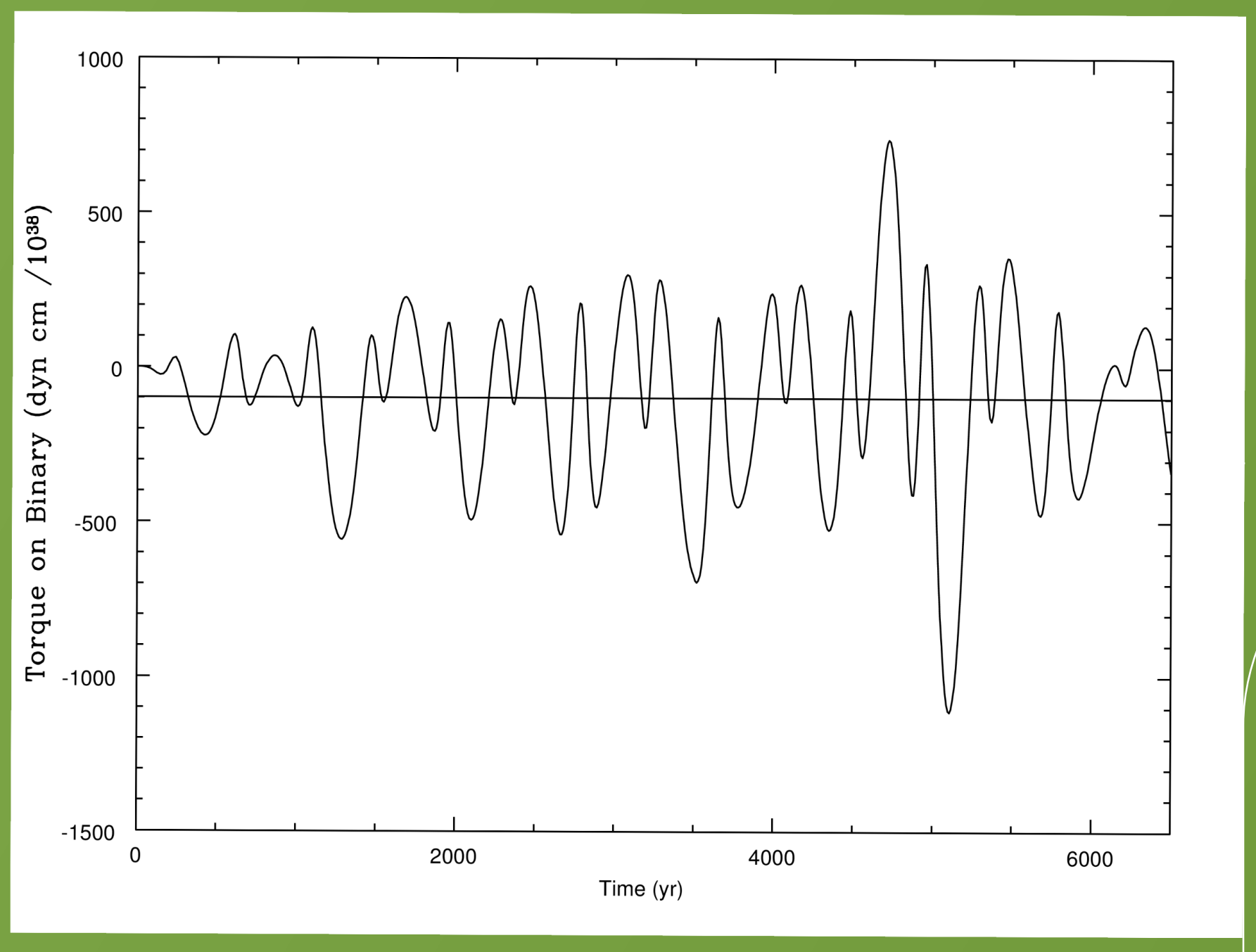


Figure 5: Torque due to the torus+disk on the stars over time, and averaged. Although highly variable on orbital timescales, **the time averaged torque is negative—driving the binary together at a rate such that it may disrupt itself within ~1Myr.**

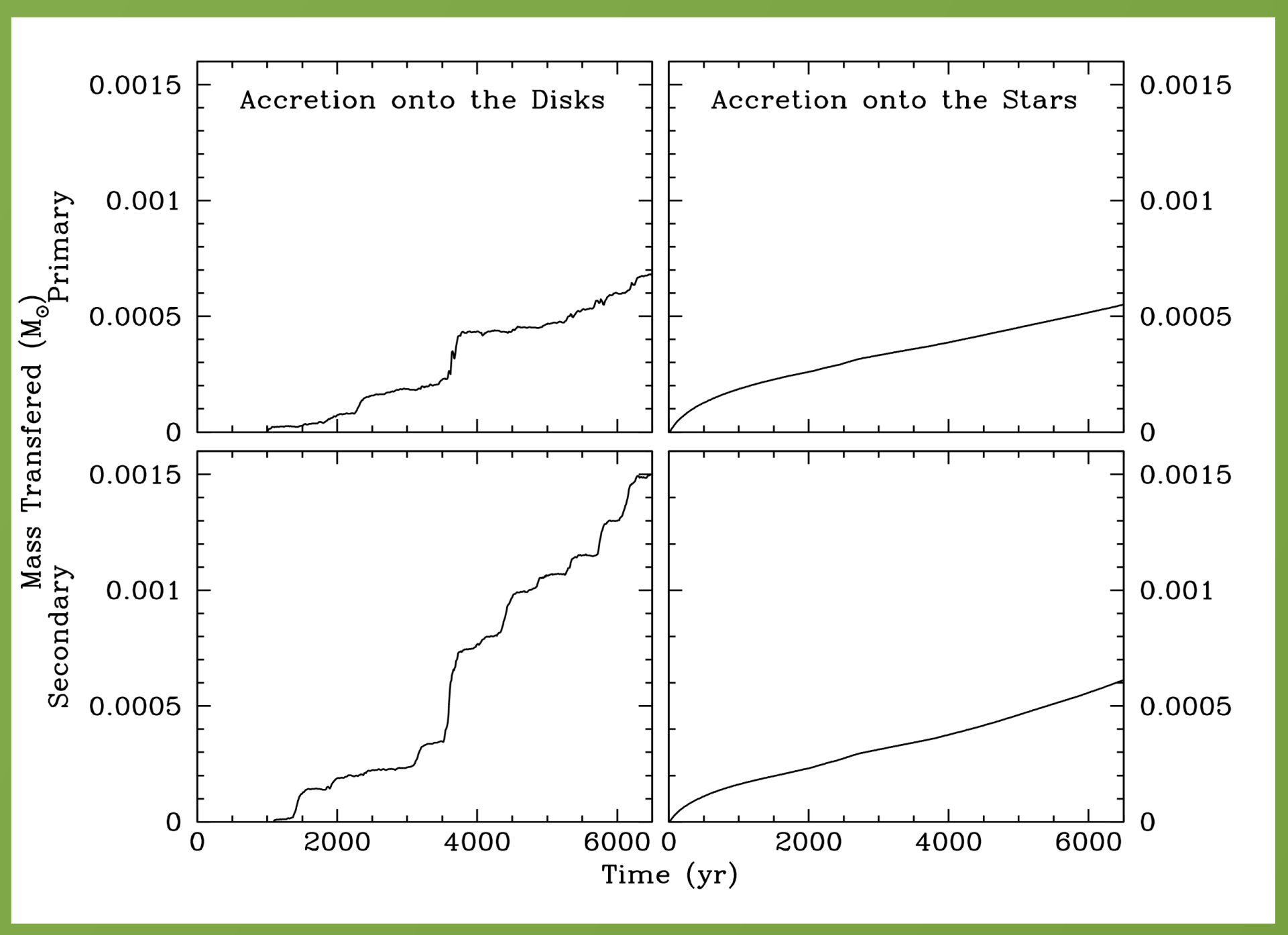


Figure 6: Mass transferred into the circumstellar disks from the torus (left) and out of the circumstellar disks by way of accretion onto the stars (right). Accretion onto the disks is maximum near periapse passages of the binary and occurs preferentially onto the secondary. Accretion onto the stars is smooth. **The long term average rates onto the stars and the disks are similar at ~1M_J/10kyr, leaving the time averaged disk masses nearly constant although material continually cycles through them.**

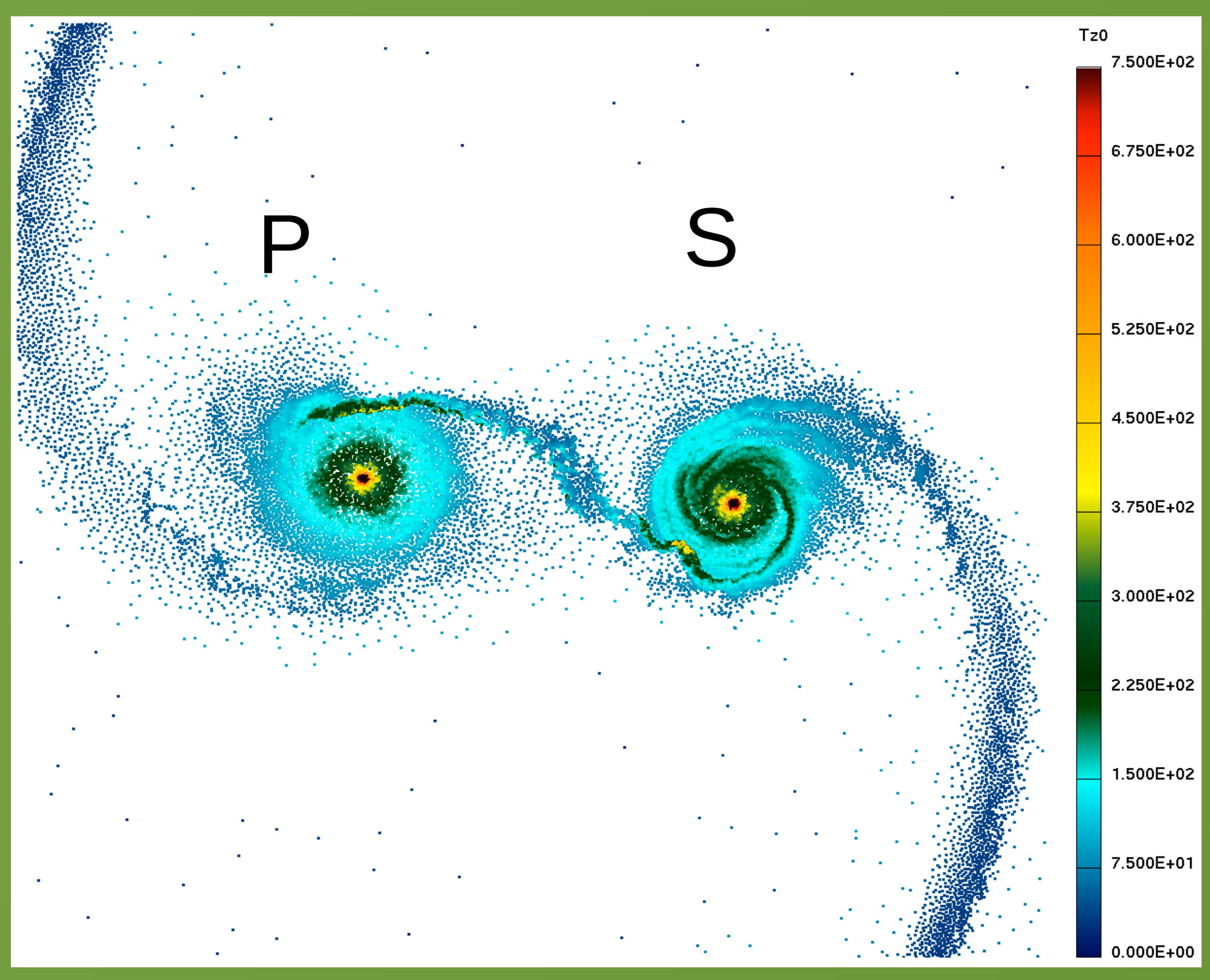


Figure 7: Midplane temperatures in the accretion streams and circumstellar disks, shown in a blowup of the configuration at the same periapse passage seen in figure 1. **High temperatures are generated in the outer disks due to shocks generated both by mass accretion and by spiral structures within the disks, arguing against the conclusion of Dutrey et al (2014), who suggest that such temperatures far from the stars may trace planet formation.**

Discussion and Implications for Planet Formation

- Spiral streams extending inwards from the torus develop during each binary orbit, with a portion accreting onto the circumstellar disks and the remainder returning to the torus.
  - Accretion is episodic onto both primary and secondary with time averaged rates ~10^{-7}-10^{-8}Msun/yr.
  - Accretion preferentially onto the secondary, but rates for both are within a factor of ~2.
  - Provides a continuing source of mass for planet building, as new material is added.
- Temperatures are ~150K or higher throughout the disks
  - Accretion shocks and episodic spiral structure generate hot spots in the outer disks and elsewhere
  - Higher temperatures suppress grain growth: No ice line!
- Accretion through the disks is rapid
  - At rates of ~$10^{-4}M_J$/yr and disk masses of ~1M_J, material accreted *into* the disks will accrete *out of* the disks within ~10^4 yr
  - Solids must decouple from the gas within this timescale or be lost to planet formation.
- If planet formation is to occur in this or similar systems, it must do so in spite of high temperatures and rapid mass loss through accretion.

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