Dissipation Timescale of Gas Disk

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Fate

A protoplanetary disk dissipates on the time scale of 3 Myr (Haisch et al. 2001; Hillenbrand 2006 for review). A disk dissipates either by the photoevaporation or by the planet formation (including grain growth in a broad sense). To understand how a disk dissipates is to understand how lucky we are being in the solar system. If the disk dissipates as the consequence of planet formation, our being here might be a part of destiny. If a star can evaporate a disk by itself, a forming planet would have had to compete with time to accrete the disk material before it is gone. Only those systems that make it in time will survive. It could be a shear luck that brought us to a successful system.

The Jupiter is more important than the Earth

The often-quoted timescale of the disk dissipation 3 Myr bases on the hot thermal dust emission at 3 μm . Although the gas dominates the disk mass over the dust grains, the timescale of gas dissipation has never been properly addressed. As the gas and the dust inevitably decouples when the density and the temperature drops down (Kamp & Dullemond 2004), the gas should dissipate by a different process in a different timescale.

Moreover, the dissipation of gas is more important than the dissipation of dust in the disk. This is because a Jupiter is more important than an Earth. A Jupiter is the architect of a planetary system. An Earth can be thrown away by a gravitational swing of a Jupiter, but not the other way around. An earth could save its life from the deadly migration inward by being traped by the resonance capture of an giant, but not the other way around.

Inner disk

A disk dissipates inside out. This is not as trivial as it may sound. A decade ago, we were inspired that the external radiation may be an integral part of disk dissipation faced at the visible demonstration by Orion proplyds (e.g. Johnston et al. 1998). The numbers of SEDs collected by Spitzer reinforced early decline of the near-infrared excess to the far infrared and submm wavelengths (e.g. Pietu et al. 2006). A few protoplanetary disks are directly resolved by SMA and PdBI with the central depressions (e.g. Brown et al. 2008). It is now uncontroversial that disk dissipates by itself without external cause, from the innermost region outward.

The vibrational transition of molecules falling in the near-infrared (1–5 μm) wavelengths is the best and perhaps only probes that works for the gas at the inner part of a disk at 0.1–10 AU. Infrared spectroscopy exclusively traces inner region where the temperature is high enough to populate the vibrationally excited levels ($\sim$1000K). It plays nicely complementary role to the radio spectroscopy which measures the rotational transition of molecules in the outer cold disk.

Current frontier

The molecular probes most frequently used are CO and H_2. The latter has seen less success for the lack of permanent dipole moment. The survey of H2 in protoplanetary disk was more successful at the UV with electronic transition, and at 12–28 μm with pure rotational transitions mostly from the space, but the positive cases are outnumbered by CO, which is almost ubiquitous under a certain age.

The diagnostics we could obtain with CO are broad (Scoville et al. 1980; Kostov et al. 1980; Carr et al. 1989 ; Najita et al. 1996). Multiple line emission gives excitation temperature and the column density of emitting gas. The fundamental transition is prone to get optically thick quicker than the overtones, giving a good handle of gas opacity. The gas mass is detectable down to 1e-5 earth mass. Line emission gives kinematics in contrast to the dust emission, which helps to locate the gas at the certain radius in a disk, and to construct the geometrical model of it. We could obtain the clues of excitation mechanism once we know how the different vibrational levels are populated.

The near infrared CO spectra has been collected by number of 10 to 20 using infrared high resolution spectrographs at 8-m class telescopes (e.g. Britain et al. 2007a). Possible interaction of planets and gas disk has been already implied by (Carr et al. 2008), who shown the orbital distribution of hot Jupiters (0.04 AU) somehow peaks close to the inner truncation of gas disks of T Tau stars, suggesting gas drag of small bodies. However, the observation has not reached the critical mass in total to draw the grand picture of gas dissipation yet.

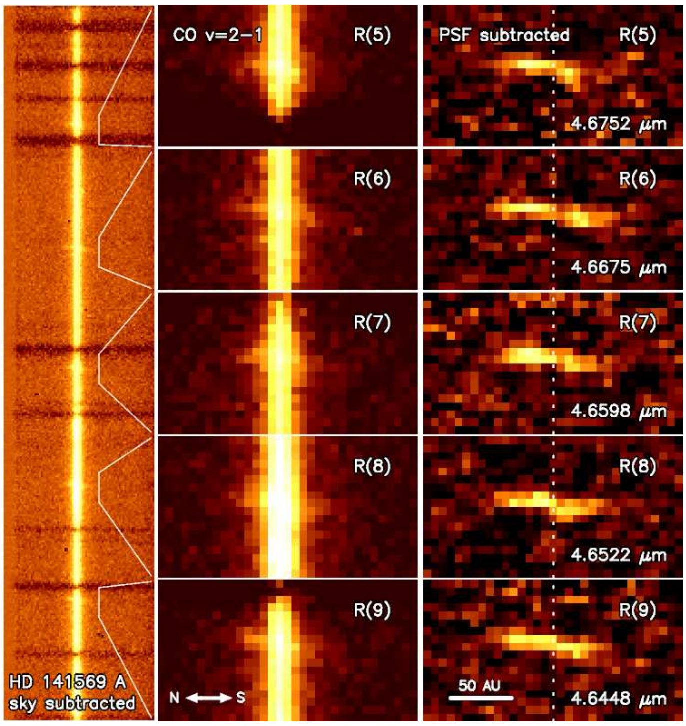

Figure 1: Two dimensional spectrogram of HD 141569A at the CO fundamental band at 4.7 μm (Goto et al. 2006). All v=2–1 emiss ion lines in the coverage are extended upto 50 AU with clear kinematics signature. The size of the central cavity is 11 AU.

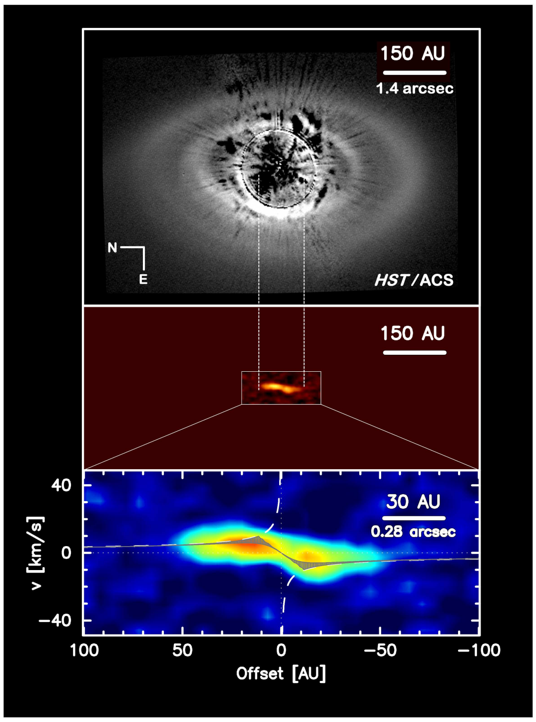

Figure 2: CO spectroscopy offers an opportunity to go beyond the state-of-the-art coronagraphy by HST (Top panel; Clampin et al. 2003).

What will come in 2010–2020

In the next decade, more and more molecular lines will be spatially resolved on the physical scale of 1 AU. The key technology here is an IFU spectrograph on 30 m class telescopes. The instrument will bring the inner 1–10 AU of a disk in dissipation under a microscope. Although reconstruction of geometrical model is still possible based on the kinematical information we can get from emission profiles, spatially resolved line image will take us to the next stage. It helps us to detect faint emission very close to the star otherwise buried in the photon noise of bright central sources. Any disk structures more than a fiducial analytical model, gaps, spirals in the disks, are only properly characterized when the disk is spatially resolved. As the dynamical timescale of a disk is about an year at 1 AU, temporal variation of disk structure associated either to FUor/EXor phenomena

(Brittain et al. 2007b), or to minor bodies falling into the star (de Winter et al. 1999), will be a real subject of observation. Moreover, the cental cavity is easy to detect when the disk is spatially resolved.

Theory predicts that the disk dissipation shifts up when the photoevaporation kicks in (Clarke et al. 2001). The photoevaporation is in operation ever since the early stage of disk evolution, working most effectively at the gravitational radius where the sound speed of ionized gas is equal to the escape velocity of the system (Shu et al. 1993; Hollenbach et al. 1994). When the viscous accretion slows down, it cannot make up the mass loss by photoevaporation any more. The gas inside the gravitational radius quickly drains to create a central hole. The opening of the cavity is an instance (10^5 yr or even faster) compared to the whole disk lifetime (10^6 to 10^7 yr). The quick transition implies a clear bifurcation of the sizes of the inner clearings, only we have means to resolve it.

The gravitational radius is about 8 AU for a solar-mass star, and it only proportional to the stellar mass. There are scattered instance that central cavities are spatially resolved by 8-m class telescopes (Fig. 1 and 2). However, they are either massive ($\sim 2M_\odot$) or exceptionally close (50–100 pc). A 30 m class telescope will extend our reach to the gravitational radius of all solar-type stars at 150 pc away ($\sim$50 mas).

Star-disk-planet interaction

Suppose that a first planet successfully formed in a protoplanetary disk. How this planet has influence on the disk evolution? For instance, is it virtually a death sentence for a disk, whose remains are quickly swept as soon as the first gas giant is formed inside? That would be an unwelcoming news for other planets yet to form. The gap in the disk that the first planet opened can stop the migration of dust grains by gas drag, creating a ring of solid material. The ring of dust grains would offer a nursing environment for the next planets to form. Disk-planet interaction therefore has a consequence to the architecture of the forming planetary system. Perhaps direct observation like above has to wait more than a decade, but some are already possible in coming few years.

Current frontier

The radial velocity survey of planets is so far limited to old systems where the chromospheric activity is lower. Next few years will see, however, high-resolution infrared spectrographs (R >20000) come online equipped with gas cell and frequency comb ready for high precision velocity calibration. Infrared Dopper technique promises high fidelity detection of RV signals in particular in the young systems, for the chromospheric lines are fainter in the infrared (Martín et al 2006). We will have an access to close-in planets in the environment where the planet formation is underway. The first report of detecting a planet in a young disk system came in last year (Setiawan et al. although different interpretation was immediately proposed by Huélamo et al). This is a sole example to date, but the infrared Doppler experiment has the potential of a breakthrough.

What will come in 2010–2020

Physics of star-disk interaction is established in 1980s by series of works by Uchida & Shibata 1984; Camenzind 1990; Königl 1991 and used to understand how jets and outflows could launch from the disks. The physical scale relevant here is $1R_*$, or 0.03 mas at 150 pc away. This is too small to spatially resolve even for a 30 m class telescope.

The key technology is again an IFU. Although the PSF of a 30m telescope is much larger (18 mas at 2 μm), one can determine the centroid of PSFs with much better accuracy (<1/100 to 1/1000 of a pix). 'Spectroastrometry' measures the location of the centroids along the wavelength near an emission line to read the kinematics out of it. An example of 2D spectroastromety is shown in Fig 3. The centroid of Br γ emission from TW Hya offsets to the north at the blue shoulder, and to the south at the red. The pair of blue- and red-shifted emission split symmetric about the central star nicely fits to the picture where a pair of accretion columns bridging the disk and the star.

A planet is a new element added to the standard picture of star-disk interaction where the ionized gas is bridged to the star by the magnetic field. Polarimetric Dopper imaging suggests a planet could play a central role to regulate the geometry of the magnetic field (Catala et al. 2007). Spectroastromety can offer even more intuitive picture of star-disk-planet interaction. If seen in the pole-on, the position angel of the pair should simply rotate synchronized to the stellar rotation. It should give a visible demonstration of disk locking at work, which is essential to the angular momentum transfer.

In the case that a planet has any significant influence on the magnetic field, we should see some modulation in the rotation of accretion columns more synchronized to the orbital period of the planet. The modulation, expected to be the phase shift of the rotation, could be accompanied by the energetic events associated to the magnetic reconnection. The observation above demonstrates that an 8-m class facility with near infrared IFU can close up to the stellar-disk interacting region upto 50 pc away. A 30m-class telescope will pull most of the nearby star forming regions within our scope.

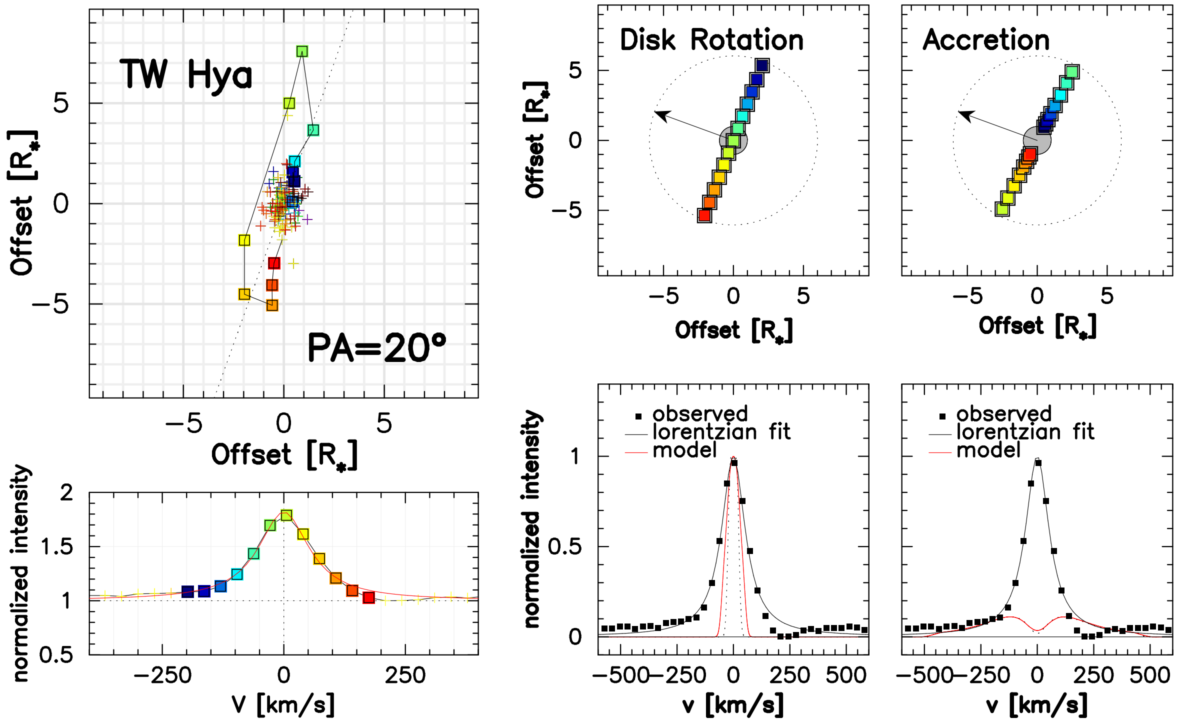

Figure 3: Left: Astrometry of Brγ emission of T W Hya as obtained with SINFONI at VLT. The emission line is red-shifted i n the south, and blue-shifted in the north along the position angle of 20°. The projected orientation and the radial motion is consistent with the disk rotation observed by CO sub-mm spectroscop y by SMA (Qi et al. 2006). However, simple model calcul ation tells the kinematics is consistent both with disk rotation and gas accretion shown in the right panels.

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