Bondi-Hoyle Accretion in Star Clusters: Implications for Stars, Disks, and Planets

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To be submitted to ApJ

Abstract

Young stars orbiting in the gravitational potential well of forming star clusters may occasionally pass through associated dense molecular gas and experience Bondi-Hoyle accretion from reservoirs unrelated to their parent cloud cores. Such post-formation accretion can occur for several million years, the time scale for cluster formation and the dispersal of surrounding molecular gas. N-body simulations of stars orbiting in three young model clusters containing comparable initial masses of stars and gas, and which contain 30, 500, and 3000 stars respectively, are presented. We find that for solar-mass stars, the total mass accreted is 1-5% of the stellar mass. The average mass accretion rate dM/dt is roughly 3 x 10^{-9} M_{sol}/yr in all three clusters, and varies roughly as $M^{2.1}$. The mass accreted is insignificant compared to the star's mass, but it is comparable to or greater than the disk mass. The accretion flow is likely to impact the disk rather than the star; the additional mass flux onto the disk may significantly affect the planetesimal and planet-formation process. The Bondi-Hoyle accretion rates are lower than those observed in young stars by a factor of 5-10, indicating that other processes also contribute to the accretion. Nevertheless, the accretion rate is high enough that it may have a substantial and unappreciated effect on the formation of planetary systems. We discuss a variety of implications of this process, including its effect on the formation of terrestrial and gas-giant planets, the tilt of the Sun, the migration of extrasolar planets, and metallicity variations between a star and its planets.

Introduction

Stars form from the collapse of dense cores in giant molecular clouds (GMCs). While some stars form in relative isolation or is small groups, the majority of stars in the sky appear to be born in transient clusters containing hundreds of members (Lada and Lada, 2003). Dense cores have masses ranging from under 1 M_{sol} to over 10^4 M_{sol} for the most massive cluster-forming environments. Self-gravity and efficient cooling by dust and molecular line radiation leads to collapse and fragmentation. The collapse time for a star in a cold cloud is roughly 10^5 year; In contrast, the observed age spread of young stars (YSOs) in clusters indicates that the formation time-scale for an entire cluster is a few million years. Thus, only about 3 to 10% of the final population of YSOs in a cluster are expected to be in their main Class 0 / Class I accretion phase at any one time.

As the cluster forms more stars, most of the oldest stars will evolve into Class II and III YSOs surrounded by protoplanetary disks. For at least a few million years, these YSOs have a chance to accrete some additional material from clumps of dense gas remaining in the region. However, the high relative velocity between a star and the gas through which it is passing will limit the amount of additional mass that can be accreted onto the star to less than a few percent of the stellar mass. Thus, `rejuvenated accretion' will have only minor consequences for the affected YSOs. But, the mass added by such secondary accretion can be large compared to the mass of its protoplanetary disk. Thus, rejuvenated accretion can have profound consequences for the evolution of very young planetary and pre-planetary systems. In this work, we explore the impacts of rejuvenated accretion on pre-planetary systems born in clustered environments.

The typical star-formation efficiency (SFE) in a cluster-forming cloud core is 10% - 40% (Elmegreen et al 2000, and references therein). Thus, the majority of the gas is not consumed by stellar birth. When only low- to intermediate-mass stars are formed, protostellar winds and jets are the most likely agents responsible for the removal of remaining gas. However, in massive cloud cores, outflows may not inject enough energy and momentum to disperse the gas, enabling star formation to continue. Furthermore, winds may increase the turbulent motions and internal pressures of the remaining gas, thereby increasing the tendency to form more massive stars (Tan & McKee 2004). When massive O and B stars form, their intense UV radiation fields are likely to dominate the termination of star formation by the removal of remaining gas. Soft UV radiation (λ > 912A) will dissociate molecules and heat cloud surfaces, raising their temperatures to 10^3 - 10^4 K. The resulting rise in the sound speed from < 1 km/s in cold molecular gas to 3 to 10 km/s in UV-heated atomic gas will cause these photon-dominated-regions (PDRs) to expand and to escape if the sound speed exceeds the gravitational escape speed. Ionizing radiation (λ > 912A) will accelerate this cloud erosion and destruction by creating expanding HII regions.

In most massive star-forming regions, UV heating and ionization will bring star formation to a halt in a crossing time which can be estimated from the radius of the region and the sound speed in photo-ionized plasma. Typically, this time-scale ranges from 10^5 to a few times 10^6 years. UV radiation may also trigger star birth, just as it halts it.

The NGC 1333 region in the Perseus Molecular Cloud (Lada et al 1996) provides a good example of a small cluster that has formed about 150 low to intermediate mass stars within the last 1 - 2 Myr. Protostellar winds appear to dominate the gas dynamics and may regulate the rate of star formation. The Orion Nebula (O'Dell 2001) is the prototypical example of a region that has spawned over 10^3 stars in a a few Myr. The dynamics of the gas is now dominated by UV radiation and winds emerging from the the massive Trapezium stars at its core. This radiation may remove most of the gas in the region within 0.1 to 1 Myr. In Orion, solar-mass stars are observed to have ages of up to 1-2 Myr, significantly older than the 10^4 - 10^5 year ages of the massive O and B stars of the Trapezium.

Stars orbit in the potential well of the cluster and will sometimes pass through the surviving remnants of its parent GMC. Stars that migrate into remaining dense gas can undergo Bondi-Hoyle accretion (Edgar 2004; Bondi & Hoyle 1944). Because the Bondi-Hoyle process scales as dM/dt ~ M^2, accretion is likely to be most important for the most massive and oldest members of a forming cluster that spend the longest time moving through dense gas. This paper focuses on roughly solar-mass stars since they are most likely to be of interest for studies of planet formation. The consequences of the late accretion of gas onto a forming planetary system are explored. The results are based on N-body simulations of the motion of stars through three model clusters which contain a large reservoir of gas which is depleted on a time-scale of several million years. The accretion of gas onto the stars and their disks is estimated using the Bondi-Hoyle formalism. Although the gas distribution is highly idealized, the results can be easily generalized to include the effects of a clumpy and turbulent medium.

Our work is the first to take a detailed look at Bondi-Hoyle accretion in clusters and its influence on circumstellar disks. Previous work by Padoan et al 2005 examined Bondi-Hoyle accretion as an explanation for observed accretion rates. Numerous previous studies have explored the dynamics of young stars within clusters, and the gravitational influence of the dispersing gas cloud (Adams et al 2006; Scally et al 2005; Kroupa et al 2001; Adams 2000; Lada et al 1984). Other modeling has studied the dynamics of the Bondi-Hoyle accretion process (Ruffert 1999; Benensohn et al 1997). Our work combines results from these three fields.

Physical Processes in Model

We consider the following processes in our model.

BONDI-HOYLE ACCRETION

Bondi-Hoyle accretion describes how gas is accreted onto a small moving mass such as a star. We assume

$$dM/dt = (4 \pi G^2 M^2 v\, n\, m_0) / (v^2 + c_s^2)^{3/2} \quad (1)$$

where

- n = local number density of the background gas (determined from N-Body simulations)
- v = stellar speed (determined from N-body simulations)
- G = gravitational constant
- m_0 = molecular mass
- M = stellar mass
- c_s = sound speed

NATURE OF THE ACCRETION FLOW

Bondi-Hoyle accretion is directed toward the central star. However, in young stars with disks, the accretion flow toward the star is intercepted by the disk. Because the disk density (~10^{12} / cm³) greatly exceeds the gas density (~10^5 / cm³ in the flow), the flow will be blocked, and the mass deposited onto the disk. Furthermore, because 80% or more of young stars have disks (Smith et al 2004), the vast majority of systems will be affected by Bondi-Hoyle accretion in this way.

EFFECT OF TURBULENCE ON ACCRETION

Equation (1) assumes a laminar, non-turbulent background gas. Real star clusters will have a non-zero turbulence, which will affect the rate of accretion of mass, and angular momentum. Modeling by Krumholz et al (2006) indicates that in cold, dark clouds such as Taurus, the effect of turbulence are relatively small, and Equation (1) is a good approximation.

INITIAL CLUSTER CONDITIONS

Initial stellar positions are randomized within a Plummer potential, with same distribution as gas. Initial stellar velocities are randomized and virialized. Stellar IMF is specified by Kroupa et al (1993), and masses do not change during the run. Mean stellar mass is 0.5 M_{sol}.

CENTRAL POTENTIAL : GAS CLOUD

We assume the cluster to orbit within a gas cloud. We use a star-formation efficiency (SFE) = 33%, where SFE = (M_{stars}) / (M_{stars} + M_{gas}). The gas has a Plummer distribution, with a Plummer radius of 0.2 pc. After a delay period, the gas mass disperses smoothly, to simulate the effect of stellar winds and radiation pressure. In our N=3000 simulation, the dispersion is the most rapid, to simulation ionization of the gas by OB stars. Dispersion is slower in the N=500 and N=30 models.

STELLAR WINDS

Stellar winds (~ 10^{-8} M_{sol}/yr) can inhibit Bondi-Hoyle accretion, but only to the extent that the accretion flow is oriented opposite the wind direction. However, winds are non-isotropic, while accretion comes from all directions. Therefore, we ignore winds, although a full treatment of the wind dynamics may reduce accretion by up to a factor of 2.

RADIATION PRESSURE

For solar-mass stars, radiation pressure is insufficient to reduce accretion. However, for high-mass stars, dust entrained within the inflow can be vaporized into a UV-opaque gas which then is prevented from accreting. Edgar and Clarke (2004) calculate that this effect is negligible below 10 M_{sol}. We therefore ignore it in this work.

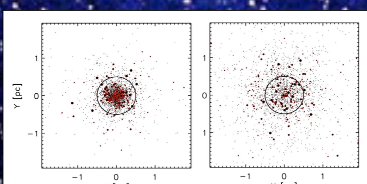
N-BODY SIMULATIONS DYNAMICS

The cluster evolution is modeled using the `NBODY6' code of Aarseth (1999). The code models the position and velocity of each star. It considers the gravitational potential of each star, and of the parent gas cloud which the stars orbit.

We compute the mass accretion in two steps. First, we perform the N-body simulation, and output stellar positions and velocities at regular intervals (10 kyr). After the run, we compute dM/dt for each star, at each step. This simplification (separating the N-body and accretion phases of the simulation) assumes that the gas mass accreted is small; during our simulations, roughly 1% of the total cloud mass is accreted. Furthermore, we assume that each star's gravitational mass remains constant during the simulation. Most stars increase in mass by < 5%, so this assumption has no significant consequences.

Input Parameters

Parameter	Small	Medium	Large
Prototype	Taurus	NGC1333 / IC348	Orion ONC
N	30	500	3000
M_{gas}	30 $M_\odot$	500 $M_\odot$	3000 $M_\odot$
Half-mass radius, stellar	0.2 pc	0.2 pc	0.2 pc
Half-mass radius, gas	0.2 pc	0.2 pc	0.2 pc
SFE	33%	33%	33%
Central stellar density (N pc^{-3})	6×10^2	10^4	10^5
Central gas density (n cm^{-3})	2×10^4	4×10^5	2×10^5
Stellar mass range	0.1 - 1.2 $M_\odot$	0.1 - 18 $M_\odot$	0.1 - 27 $M_\odot$
Mean stellar mass	0.5 $M_\odot$	0.5 $M_\odot$	0.5 $M_\odot$
Gas dispersal delay time	2.5 Myr	1.5 Myr	1.5 Myr
End time	5 Myr	2.5 Myr	2 Myr



N-BODY SIMULATIONS

Plotted are two snapshots from our 'Large' cluster N-body simulation, with N=3000. Images are at t = 0, and t = 2 Myr. The cluster has spread due to gas loss, and due to high-mass stars settling toward the cluster core. The large circle indicate the position inward of which 90% of the mass starts.

Implications and Applications

Rejuvenated Bondi-Hoyle accretion can have significant effect on the evolution of disks, because it provides a source for ongoing material that accretes to the disk for several Myr after the disk has formed. This accretion happens while planetesimals and planets are forming, but before the disk has dissipated. Accreted material in the disk can have a different composition and angular momentum than the original disk, and it is accreted over a much longer timescale.

We propose a number of areas where this process could have substantial impact on the the star, the disk, and planets. We present these as directions for future research; none of them have yet been modeled in detail.

COMPOSITION DIFFERENCES BETWEEN STAR, AND DISK-PLANETS

If the composition of the rejuvenated flow is the same as that of the original cloud, then the star's metallicity will not change. However, because rejuvenated accretion onto the star samples a great swath of time and space across the cloud, the star could sample regions of different metallicity. Variations are expected in clouds due to dust concentration mechanisms (Padoan et al 2006), and supernovae. Observations by Cunha et al (1998) find composition differences in Fe, O, and Si of 4x between similar-mass in the Orion Ic association, apparently correlating with spatial composition differences in the gas cloud.

The rejuvenated accretion scenario provides a natural extension of this: mass accreted onto a disk can have different composition than the star. In our own solar system, Jupiter is enhanced by 3-10x over the Sun in most metals (Atreya et al 2003). This difference could be explained if the young Solar System disk accreted relatively `clean' material after formation of the Sun. This low-metallicity material would be incorporated into the planets, while making minimal effect on the composition of the Sun. The magnitude of the metallicity change required is comparable to the compositional gradient observed across Orion.

FORMATION OF PLANETS

The rejuvenation accretion scenario increases by up to 5x the amount of mass available for the formation of planets, because additional mass is accreted onto the disk during the first 1-5 Myr. This may increase a disk's lifetime, its mass at a given time, or both. An obvious implication is that this process increases the probability of forming planets, by allowing for planet formation under a broader range of scenarios. The precise details remain to be modeled.

MIGRATION OF PLANETS

Gas drag by a disk can cause radial migration of planets. Many planetary systems have been found very close to their host stars, suggesting that they migrated inward from regions of higher density where they were formed. Migration could be caused by a gas disk; however, such a disk requires a rapid dispersal mechanism in order to halt the migration. Photo-evaporation by the central star (Matsuyama et al 2003) has been proposed as one such mechanism.

Rejuvenated accretion could also cause such a situation. Inward migration of planets and/or planetesimals would be caused by a tenuous gas disk. However, such a disk could be rapidly dispersed by the as the gas cloud is heated and removed. Thus, planet migration would cease rapidly, leaving planets at a fixed position close to their host star.

CIRCULARIZATION OF TERRESTRIAL PLANET ORBITS

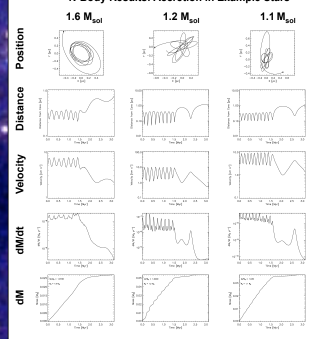
Models for the formation of the solar system have difficulty explaining the low eccentricity of the terrestrial planets. In order to collisionally grow, planetesimals in the terrestrial planet zone require high eccentricities. However, the planets today have low eccentricities (e ~ 0.001), and these cannot easily be explained without a damping mechanism of unknown origin. Agnor & Ward (2002) suggested that the eccentricities could be damped by a relatively long-lived remnant gas disk. They computed that a disk of surface density ~ 10^{-3} - 10^{-4} that of the MMSN, and surviving for 10^{-6} - 10^{-7} years, would provide the necessary damping mechanism. The rejuvenated accretion scenario provides a natural source for this long-lived, tenuous disk.

TILT OF THE SUN

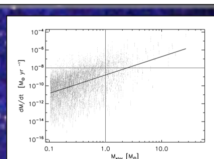
The Sun tilts at a 7 degree angle relative to the plane of the solar system. The source of this tilt is generally unexplained. Accretion of the Sun-disk system from a single cloud would be expected to form a Sun closely aligned with the disk. Accretion of the planetesimal disk onto the Sun provides insufficient mass to significantly alter the Sun's tilt.

Rejuvenated accretion could provide an explanation. In this scenario, accretion of angular momentum from the cloud would provide a weak but long-lived torque on the disk. The accreted angular momentum is of essentially random orientation, with no preference to be aligned with the disk's existing angular momentum vector. Because the accreted mass (and angular momentum) is comparable to that of the original disk, the disk's final orientation would be different than that of the Sun.

N-Body Results: Accretion in Example Stars

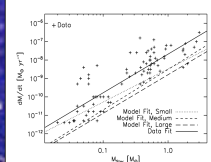


Plotted above are orbits for three sample stars in our Large cluster simulation. We use NBODY6 to compute the stars' **Position** and velocity at each timestep. Each stars' orbit expands as cluster gas is lost, although most stars are not lost during our runs. The **Distance** from the core determines the local gas density of the molecular cloud. The density and the **Velocity** are used to compute the Bondi-Hoyle accretion, **dM/dt.** Finally, the total mass gain, **dM**, is computed by summing dM/dt. Most of the mass accretion occurs during brief, episodic passes near the cluster core, where the density is highest. Accretion also peaks at apoapse, where the velocity is lowest. These stars (or their disks) gain 2%, 4%, and 3% of their original mass; in all cases the accreted mass exceeds the MMSN disk of 0.01 M_{sol}.



ACCRETION RATE VS STELLAR MASS: MODEL

Plotted are instantaneous dM/dt for each of 3000 stars in our 'Large' N-body simulation, at each of 600 timesteps. The solid line is a fit to the data, with dM/dt ~ $M^{2.1}$. The scatter is due to variations in each star's position and velocity within the cluster. High mass stars lie slightly above the line, because they settle to the cluster core, where velocities are damped and densities are higher.



ACCRETION RATE VS STELLAR MASS: OBSERVED

Plotted on are observations of Muzerolle et al (2005): '+' symbols and solid line. Our model results are plotted in the three dot/dashed lines. The computed accretion rates are consistently ~5-10x too low to explain the observations. Bondi-Hoyle accretion may contribute indirectly to observed accretion, but it cannot be the sole source of it.

Results

MASS ACCRETION RATES ONTO STAR-DISK SYSTEMS

The figures above display the orbits, velocities, and accretion rates for three sample stars from our Large cluster. Stars from the other clusters are similar. Typical stellar velocities are 1-10 km/sec. When passing through the cluster core, accretion rates for solar-mass stars are 10^{-9} – 10^{-8} M_{sol} / yr. The accretion is highly episodic. The highest accretion rates occur near the cluster core (where the density is highest), although peaks occasionally occur at aposapse (where the volocity is lowest).

Best fits for the accretion rate are:

- Small: dM/dt = 3.3 x 10^{-9} $(M/M_{sol})^{1.8}$ M_{sol}/yr
- Medium: dM/dt = 3.0 x 10^{-9} $(M/M_{sol})^{2.2}$ M_{sol}/yr
- Large: dM/dt = 1.6 x 10^{-9} $(M/M_{sol})^{2.1}$ M_{sol}/yr .

Fits for the total integrated mass accreted by a star during the simulation are:

- Small: 0.05 $(M/M_{sol})^{1.2}$ M_{sol}
- Medium: 0.02 $(M/M_{sol})^{1.2}$ M_{sol}
- Large: 0.02 $(M/M_{sol})^{1.0}$ M_{sol}.

The total mass accreted is insignificant compared to the stellar mass, but is comparable to the disk mass. Because the disk blocks the accretion flow, most of the mass is expected to flow onto the disk. Rejuvenated accretion adds roughly one minimum-mass solar nebula (MMSN) disk per Myr. For small disks, the accretion amount onto the disk may exceed the disk's original mass by several times.

COMPARISON WITH OBSERVATIONS

Observations of young stars of age several Myr have consistently measured stellar accretion rates which scale with stellar mass: dM/dt ~ M^2, with dM/dt = 10^{-8} msol/yr for solar-mass stars. The relationship has been observed in several hundred stars over the mass range 0.01 M_{sol} - 3 msol (e.g., Natta et al 2006; Muzerolle et al 2005; Sicilia-Aguilar et al 2005). There is a large amount of scatter, with values of dM/dt for comparable values of M varying by 10^3 times. The scatter is intrinsic and not an observational effect.

Fits to observations of accretion presented in Muzerolle et al (2005) yield:

Obs: dM/dt = 21 x 10^{-9} $(M/M_{sol})^{2.1}$ M_{sol}/yr

Bondi-Hoyle accretion reproduces the slope of the data (dM/dt ~ M^2), and its broad scatter (~1000x), which is an intrinsic feature to both the data and the observations. These trends match over a factor of close to 100 in stellar mass. However, the observed rates are consistently ~5-10x higher than the rates we calculate.

This is not unexpected, because the observation measure the disk-to-star accretion rate, while our simulations compute the cloud-to-disk rate. These would only be equal in a steady-state disk, and observations of disk dispersal indicate that disks are clearly not steady-state.

Other mechanisms for disk accretion already exist, although none have successfully reproduced the dM/dt ~ M^2 relationship. Rejuvenated accretion is several times too low to explain the observed accretion rate onto the star. However, it may have an indirect influence on the observation accretion rates, by providing substantial additional mass that is later accreted onto the star. The disk acts as a temporary buffer between these two types of accretion.

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