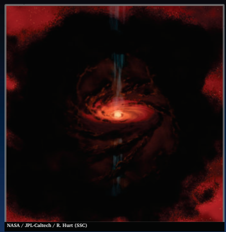
Dust Enrichment of Interstellar Molecular Clouds from Young Stellar Jets



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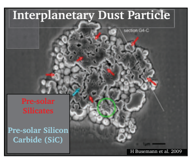
Introduction

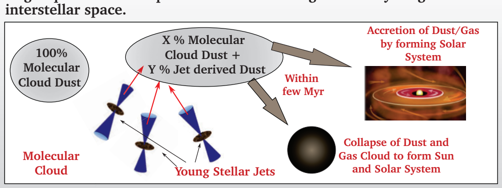
Planetary systems, including our solar system, arise as a natural byproduct of the process of star formation in interstellar molecular clouds. Such clouds consist mainly (> 95%) of hydrogen H_2, helium and other light molecular gases, and a small fraction of sub-micrometer-sized solid dust grains. The inner rocky planets, moons, and asteroids of our solar system, including the Earth, ultimately formed out of that dust component. Thus, understanding the sources and evolutionary history of those tiny dust grains is critical to understanding the formation of our solar system in general and our Earth in particular.



Meteorites enable us to study the formation and earliest evolution of our solar system because they preserve dust grains that existed prior to the formation of the planets, some of it heavily processed by high temperature processes near the Sun but some of it preserved intact from the interstellar gas cloud before the sun was born. Most of the studied pre-solar grains are chemically resistant phases like diamond, graphite, SiC and not the silicate dust which forms the bulk of the Earth and other rocky planets. Those grains have been identified by their extreme isotopic compositions, far unlike anything found on Earth, and formed in exotic environments like supernovae, novae, and planetary nebulae. Yet astronomical observations have shown that silicate dust grains are the dominant component of the Interstellar Medium Dust (ISM Dust), the dust which later gets incorporated into the molecular clouds and ultimately into planetary systems. Some silicate grains have been similarly identified, in micrometeorites and meteorites, providing evidence that the pre-solar silicates were not preferentially destroyed by the high temperature processes everywhere in the solar system, especially near the Sun. So, what happened to the pre-solar silicates which theories predict should exist in large quantities? It is possible that they are actually present but we cannot recognize them because they are not isotopically bizarre. How could this be?

One proposal to explain this problem is based on dust transport by bipolar jets/outflows, which are widely observed to occur in young stars (See Star Formation Model, Macpherson & Boss, 2011). These jets eject large quantitites of processed dust and gas from young stars into interstellar space.

1 Astronomical Unit (AU) : Average Distance between Earth and Sun
1 parsec (pc) ~ 2×10^5 AU ; 1 pc = 3.26 light-years



Dust Enrichment Model

The bulk isotopic composition of jet outflow dust grains is expected to be almost indistinguishable from dust grains formed in the solar system as they formed in same region of molecular cloud. Thus, the lack of detected silicate pre-solar grains is because the isotopic variations used to distinguish pre-solar material from early solar system dust are too small to measure.

In order to test this model, an accurate estimate of the dust transport by outflows is required. Based on previous studies (Tielens et al. 2005, Dwek et al. 1980), estimates of dust enrichment of ISM by outflows vary widely ranging from greater than 30 % to less than 15%. However, these estimates did not include a detailed analysis of dust and jet dynamics.

The primary objective of the research project is to calculate how much dust a young stellar jet can deposit in the local interstellar medium.

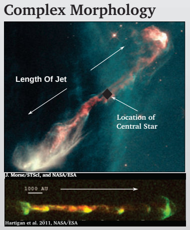
Jet Properties

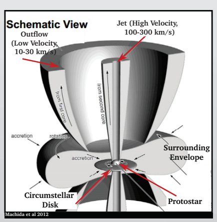
Definition of a Jet : A Collimated beam of matter (Primarily Dust and Gas) moving at high velocity away from a star's rotational poles

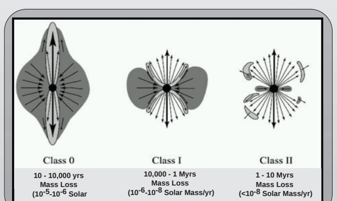
- Launched from very close to the central protostar
- Time Duration : 10^4 - 10^6 yrs
- Mass Loss Rate (dM/dt) : 10^{-5} - 10^{-9} Solar Mass/yr (3.0 * Earth Mass - Mass Asteroid Belt)

  This is about 2-10% of the material accereted onto the star through the surrounding disk
- Average temperatures of the gas : ~ 10^4 Kelvin (with spatial variation)
- Have Complex Morphology
- Length Scale (From Base to Final Shock Region) : 1- 10 pc
- Average gas density : 10^{-16} - 10^{-20} gm/cm^{-3}
- Opening angle, defined as jet width divided by distance from the source, is ~ 2-5^o . Thus, the jets are highly collimated
- Jet launching mechanism - Action of a large scale magnetic field threading the proto-planetary disk

The jets are very energetic and can influence the surrounding cloud changing its structure and composition and thus dramatically affect star formation in the region (Ray 2007)



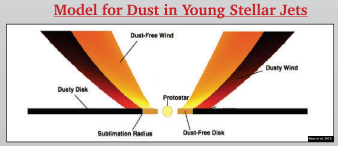




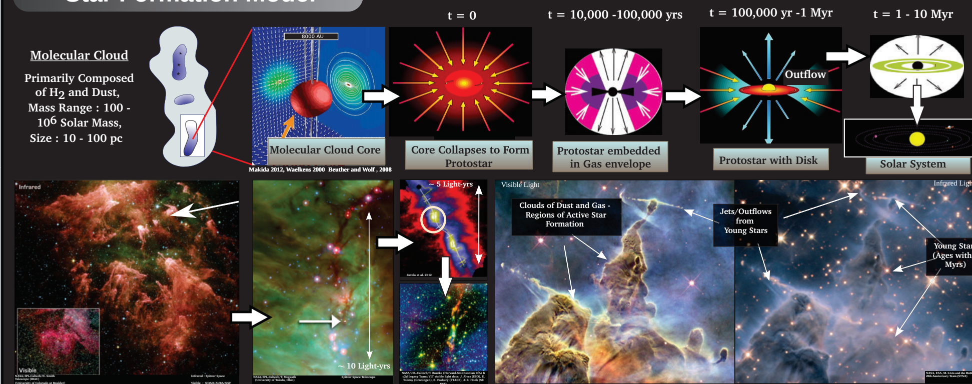
Dust Content of Jets

Dust has been not been directly observed in young stellar jets but there is indirect evidence of its presence based on depletion in gas phase of certain elements like Ca, Fe with respect to the expected solar abundance (Agra-Amboage et al. 2011). The likely explanation for this depletion is the presence of dust grains with minerals containing these elements. However, as these observations are sensitive primarily to the shock regions, overall jet dust mass fraction is unknown.

Model for Dust in Young Stellar Jets



Star Formation Model

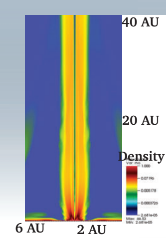


Numerical Simulations

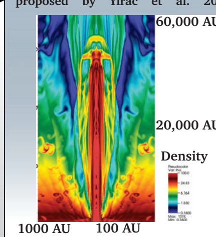
The evolution of a young stellar jet from its initial launching phase to its large-scale propogation was calculated using nested 2-Dimensional MHD (Magneto-Hydrodynamics) numerical simulations. As the dust/gas mass fraction in the jet is expected to be below 1/100 based on observations of the underlying disk, our simulations consider only gas dynamics and the dust particle trajectories are calculated separately.

Components of the Numerical Model :

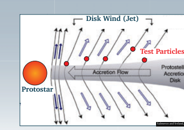
Disk Wind Jet model : Time evolution simulations of young stellar jet based on a model proposed by Fendlt et al. 2008, which reproduces the various observed jet properties.



Long-Duration Simulations : Using results from Close-in simulations, calculation of the long-term evolution of jets and their interaction with the surrounding molecular cloud using a model proposed by Yirac et al. 2012.



Dust Particle Trajectories and Temperature : Test particles, representing dust grains, are injected into the jet at different radial distances close to the underlying disk . Using gas dynamics results from simulations, particle trajectories are computed taking into account gas drag forces. Additionally, the particle temperature is self-consistently calculated by considering gas-grain collisions.



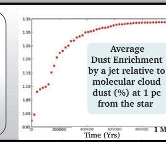
Ejected Grain Size < 10 microns

Overall Dust Mass Flux : Assuming a constant dust to gas mass ratio, particle trajectories starting from different radial distances at the base of the jet are scaled by the gas number density at that location to estimate dust flux over time.

- As jet strucuture evolves to quasi-stationary state within ~ 10000 yrs in our models, results were calculated assuming a time-varying Jet Mass flux with a functional form consistent with observationally measured timescales
- Constant Dust/Gas mass ratio of 1/100
- Physical Effects included :
  1) Dust Destruction by Shock Waves
  2) Interaction of Jet with Molecular Cloud and Jet Variability

Preliminary Result :

Averaging over distances between 1-10 pc from the stellar source, a single Jet can constribute about 1-5% of the total Dust in molecular cloud and thus 10 stars would enrich the medium by 5-20 % per pc^3 over a time period of 1 Myrs.



Future Work:

- Performing Higher Resolution Simulations to validate results
- Using Different Jet Models to test robustness of results
- Including a model of the Molecular Cloud to estimate dust enrichment by multiple young stellar jets

References and Acknowledgement

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