Formation of chondrules in wind-driving disks

Raquel Salmeron

Research School of Astronomy & Astrophysics
Research School of Earth Sciences
Mathematical Sciences Institute
The Australian National University

collaborators
Mark Wardle, Arieh Königl, Trevor Ireland
Protostellar outflows

- Bipolar molecular outflows and atomic jets are ubiquitous phenomena in protostars
  - $V_{\text{jet}} \sim 150 - 400 \text{ km s}^{-1}$
  - $M_{\dot{\text{m}}} \sim 10^{-9} - 10^{-7} \text{ M}_{\odot} \text{ yr}^{-1}$
  - Opening angles $\sim 3 - 5$ deg on scales of $10^3 - 10^4$ AU
  - Onion-like morphology
- Strong correlations between outflow and accretion diagnostics

The Dynamic HH 30 Disk and Jet
Hubble Space Telescope • WFPC2

NASA and A. Watson (Instituto de Astronomía, UNAM, Mexico) • STScI-PRC06-32b
Accretion-outflow correlation

Outflows can efficiently extract angular momentum from the disk, enabling material to accrete.
• “Energy and angular momentum may be removed magnetically from accretion discs, by field lines that leave the disc and extend to large distances”

• “A centrifugally-driven outflow of matter from the disc is possible, if the poloidal component of the magnetic field makes an angle of less than 60° with the disc surface”

• “Magnetic stresses can extract the angular momentum from a thin accretion disc and enable matter to be accreted”
Jet launching radius

\[ \frac{v_{p, \infty}^2 + v_{\phi, \infty}^2}{2} = \Omega_0 (v_{\phi, \infty} r_\infty) \]

Energy

Ang. momentum

**TABLE 4**

**Launch Point of the Disk Wind**

<table>
<thead>
<tr>
<th>Star</th>
<th>Jet Lobe</th>
<th>( \varpi_\infty ) (arcsec)</th>
<th>( \varpi_\infty ) (AU)</th>
<th>( \Delta v_{\text{rad}} ) (km s(^{-1}))</th>
<th>( v_{\text{rad}} ) (km s(^{-1}))</th>
<th>( \varpi_0 ) (AU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TH 28</td>
<td>Redshifted</td>
<td>0.1–0.2</td>
<td>1–34</td>
<td>10–25</td>
<td>30–20</td>
<td>0.3–1.6</td>
</tr>
<tr>
<td></td>
<td>Blueshifted</td>
<td>0.1–0.2</td>
<td>17–34</td>
<td>8–15</td>
<td>50–40</td>
<td>0.1–0.4</td>
</tr>
<tr>
<td>RW Aur</td>
<td>Redshifted</td>
<td>0.1–0.2</td>
<td>14–28</td>
<td>10–25</td>
<td>105–100</td>
<td>0.4–1.3</td>
</tr>
<tr>
<td></td>
<td>Blueshifted</td>
<td>0.05–0.1</td>
<td>7–14</td>
<td>10–25</td>
<td>180–170</td>
<td>0.1(^a)–0.4</td>
</tr>
<tr>
<td>LkH(\alpha) 321</td>
<td>Blueshifted</td>
<td>0.05–0.1</td>
<td>27.5–55</td>
<td>5–12</td>
<td>390–380</td>
<td>0.1(^a)–0.2</td>
</tr>
</tbody>
</table>

**Notes.**—The range for the launch point of the disk wind, \( \varpi_0 \), for our five targets, calculated using the method described in Anderson et al. 2003.

\(^a\) Where emission is faint values for the 0\(^\prime\)05 position were used, but these should be considered less accurate because of resolution constraints.

Inferred launching radius \( \sim 0.1 - 1.6 \) AU
Radially-localised wind-driving disk solutions

\[ a_0 = 0.75, \ \epsilon = 0.1, \ \epsilon_B = 0 \]

\[ R = 1 \text{ AU}, \ \Sigma = 600 \text{ g cm}^{-2} \]

Wardle & Königl (1993); Königl, Salmeron & Wardle (2010); Salmeron, Königl & Wardle. (2011); Königl & Salmeron (2011)
Outflow criteria
(Ambipolar diffusion, Hall sub-regime)

(1) The fluid is sub-Keplerian in the disc region

(2) Wind-launching condition: \( B_t / B_z > 3^{-1/2} \)

(3) The base of the wind lies above a density scale-height.

\[
(2\Lambda)^{-1/2} \lesssim a \lesssim \sqrt{3} \lesssim \epsilon \Lambda
\]

\( \Lambda \) Field-matter coupling parameter \( (v_A^2/\eta\Omega) \)
\( a \) Field-strength parameter \( (v_A/c_s) \)
\( \epsilon \) Normalized inward radial speed at \( z = 0 \) \( (-v_{r0}/c_s) \)

Wind properties vs disk parameters

Wind properties and field polarity

\[ \frac{\eta_0}{\rho_0} = 0.01 \quad \frac{\eta_p}{\rho_0} = 0.6 \quad |\frac{\eta_H}{\rho_0}| = 0.8 \]

- \( B_z < 0 \)
- \( B_z > 0 \)

\[ \left| \frac{v_r}{c_s} \right| = 1.5 \]

- 1.0
- 1.5

- 2.0
- 3.5
- 4.5

Ion-neutral coupling (\( \Lambda/\beta_i \))

Wind properties and magnetic diffusion

\[ a_0 = 1 \quad \Lambda_0 = 5 \quad c_B = 0 \quad \tilde{\eta}_0 = 0.01 \]

- Ambipolar diffusion (AD)
- \( AD = \text{Hall case} \)
- \( \tilde{\eta}_0 = 0.01 \)

Inward speed at the midplane (\( \varepsilon \))

\[ \beta_j = \frac{eB}{m_j c \gamma_j \rho} \]

\[ j \quad \{ \begin{array}{l} i = \text{ions} \\ e = \text{electrons} \end{array} \]
JED: Jet-Emitting Disk
SAD: Standard Accretion Disk (MRI)
Chondrite meteorites

- The “building blocks” of the solar system, out of which the planets form.

- Chondrules are millimetre-sized sub-spherical assemblages of magnesium-silicate minerals, mainly olivine and pyroxene.

- Their texture and mineralogy suggest that they were once molten in the solar nebula, with melting temperatures of the order of 1800 K required to explain their properties.
Conditions of chondrule and chondrite formation

- Size range of ~ 0.1 to 1 mm
- High fraction of the volume of chondrites
- Initial temperature ~ 400K or less
- Peak temperatures ~ 1700 – 2000 K.
- Rapid cooling ~ 10 – 1000 K/hr.
- Complementary composition of chondrules and matrix

LL3 Semarkona.

Chondrule formation models

- Hot solar nebula
- Lightning strikes
- Protoplanetary collisions
- Shock waves
- X-wind

e.g. see reviews by Ciesla 2005, Jones et al. 2000, Rubin 2000, Scott & Krot 2005.
Chondrule formation
X-wind

Shu et al (2001)
Chondrule formation
X-wind

- No solid material at ~ 0.1 AU
- Complementarity excluded
- Efficiency of formation
- Particles cannot escape being accreted
- Trajectories not modelled in detail

Desch et al. (2010); Hezel & Palme (2008)
Conditions of chondrule formation

- Size range of ~ 0.1 to 1 mm
- High fraction of the volume of chondrites
- Initial temperature ~ 400K or less
- Peak temperatures ~ 1700 – 2000 K.
- Rapid cooling ~ 10 – 1000 K/hr.
- Complementary composition of chondrules and matrix

Salmeron & Ireland (2012)
Dust processing in a wind-driving disk

Passive disk

Wind-driving disk

\[ m_p \frac{dv_p}{dt} = \pi r_p^2 \frac{C_d}{2} \rho_g (v_g - v_p)^2 - m_p \Omega_K^2 z_p \]

\[ \frac{dm_p}{dt} = \Lambda_{dg} \pi r_p^2 \rho_g |v_g - v_p| \quad \frac{dz_p}{dt} = v_p \]

Salmeron & Ireland 2012 and in prep.

\[ \rho_p = 3.6 \text{ g cm}^{-3} \]
\[ C_p = 10^7 \text{ erg g}^{-1} \text{ K}^{-1} \]
\[ \Lambda_{dg} = \text{dust-to-gas mass ratio} = 0.01 \]

Hood & Horanyi 1995; Dullemond & Dominik 2005
Chondrule formation in a disk wind

\[ m_p C_p \frac{dT_p}{dt} = 4\pi r_p^2 \rho_g C_H |v_g - v_p|(T_{\text{rec}} - T_p) + \pi r_p^2 \epsilon_{\text{abs}} J - 4\pi r_p^2 \epsilon_{\text{em}} \sigma T_p^4 \]

\( T_{\text{rec}} \) = recovery temperature.
\( C_H \) = Heat transfer function

Salmeron & Ireland (2012)

Hood & Horanyi (1995)
Chondrule formation in a disk wind

\[ R = 1 \text{ AU} \]
Chondrule formation in a disk wind

- Size range of ~ 0.1 to 1 mm
- High fraction of the volume of chondrites
- Initial temperature ~ 400K or less
- Peak temperatures ~ 1700 – 2000 K.
- Rapid cooling ~ 10 – 1000 K/hr.
- Complementary composition of chondrules and matrix

- Balance of grain-gas drag and gravity leads to selection of particles in a tight size range
- Continued operation of a disk wind results in greater processing of disk material.
- The final particle temperature is not strongly dependent on the initial temperature (ca. 400K).
- Disk wind rapidly heats particles within the 0.01 - 0.1 cm size range to required temperatures.
- Calculated rates (~ 1 K/hr) in qualitative agreement with inferred rates.
- Complementarity can be maintained because the processed material remains local to the wind region.
Conclusions

- We have devised a scheme for modelling wind-driving protostellar discs with a realistic vertical ionisation and diffusivity structure.

- We have derived parameter constraints for physically-viable wind solutions to exist.

- Numerical solutions are in agreement with these constraints and strongly dependent on the fluid conditions within the disk.

- Meteoritic evidence suggests extensive thermal processing of material in the early solar system. High and low temperature material remain in association.

- Processing of chondrule precursors at 1-3 AU in disc-winds can produce temperatures in the appropriate regime and explain basic properties of chondrule material. More modelling is warranted.
Job opportunity

- **Postdoctoral Fellow/Research Fellow in Astrophysics** at The Australian National University

- 2-year, fixed-term, research-only position funded by the Australian Research Council.

- **Topic:** theoretical and numerical studies relating to the physics of accretion disks surrounding young stars in collaboration with Raquel Salmeron and Mark Wardle.

- For additional information please contact Raquel or Mark; Applications to be submitted through the ANU website ([http://jobs.anu.edu.au](http://jobs.anu.edu.au)) before 29 July 2012