Disks around young stars

Andrea Isella
From cores to disks to planets

Andrea Isella :: Ten years of VLTI: from first fringes to core science :: Garching, October 24th
Inner disk dispersal time scale

Hernandez et al. (2008)
Thermal disk emission

Andrea Isella :: Ten years of VLTI: from first fringes to core science :: Garching, October 24th
Thermal disk emission

Andrea Isella :: Ten years of VLTI: from first fringes to core science :: Garching, October 24th
Physics in the inner disk

- planet formation and planet-disk interaction
- crystallization of dust and composition of meteorites (e.g. CAI)
- dust sublimation (effects the global disk structure, the formation and migration of planets)
- disk-star connection, jets and winds (regulate the angular momentum of the disk and star)
- accretion (regulate the final stellar mass, depends on the magnetic field and disk viscosity)
Planet formation

How much material is available to form planets? What is its composition and kinematics? How this material is radially distributed? Where in the disk do planets form? When do planets form?

Observe the location and evolution of the gas and dust

Andrea Isella :: Ten years of VLTI: from first fringes to core science :: Garching, October 24th
LkCa15: a planetary system in formation

Time = $0 \times 10^5$ yr

Surface density (g/cm$^2$)

Radius (AU)

Andrea Isella :: Ten years of VLTI: from first fringes to core science :: Garching, October 24th
LkCa15: a planetary system in formation

K5 – 1 Msun – 2-5 Myr in the Taurus Molecular Cloud

CARMA observations

<table>
<thead>
<tr>
<th>1.3 mm continuum emission</th>
<th>20 AU</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.15&quot;</td>
</tr>
</tbody>
</table>

Keck observations

Image reconstructed using the closure phase, i.e., insensitive to point-symmetric emission

LkCa 15

Krauss & Ireland (2011)


CARMA observations

Andrea Isella :: Ten years of VLTI: from first fringes to core science :: Garching, October 24th
LkCa15: a planetary system in formation

the inner disk can be investigate using the VLTI

the inner disk can be investigate using the VLTI

Inner disk from 0.2-4 AU
Gap from 4-13 AU
Giant planet at 8 AU?

Benz, Benisty, Panic

Dust in the inner disk is similar to comets ... But comets are found in the outer Solar system .. A process to circulate the dust is required

this requires temperature > 900 K, which naturally occurs in the innermost part

Eventually, the dust may sublimate ... Strong opacity discontinuity .. Nex slide
Dust sublimation:
the inner rim of the dusty disk

\[ T(r) = T_{evp} \approx 1500K \]

Millan-Gabet et al. (2001)
Tuthill et al. (2001)
Natta et al. (2001)
The “puffed-up” inner rim model

Andrea Isella :: Ten years of VLTI: from first fringes to core science :: Garching, October 24th
The “puffed-up” inner rim model

Dullemond, Dominick & Natta (2001)
Isella & Natta (2005)
Vinkovic et al. (2006)
Tannirkulam et al. (2007)
Kama et al. (2009)

SINGLE GRAIN SIZE and COMPOSITION, NEGLIGIBLE GAS OPACITY

Kama et al. (2009)
Pollack et al. (1994)

Isella & Natta (2005)
Vinkovic et al. (2006)
Tannirkulam et al. (2007)
Kama et al. (2009)

Andrea Isella :: Ten years of VLTI: from first fringes to core science :: Garching, October 24th
The “puffed-up” inner rim model

Dullemond, Dominick & Natta (2001)
Isella & Natta (2005)
Vinkovic et al. (2006)
Tannirkulam et al. (2007)
Kama et al. (2009)

MULTI SIZE and COMPOSITION DUST GRAINS, NEGLIGIBLE GAS OPACITY

Andrea Isella :: Ten years of VLTI: from first fringes to core science :: Garching, October 24th
The “puffed-up” inner rim model

<table>
<thead>
<tr>
<th>N_{mod}</th>
<th>\Sigma_0</th>
<th>\text{Olivine}</th>
<th>\text{Fors}</th>
<th>\text{Iron}</th>
<th>\text{Cor}</th>
<th>R_{rim}/[AU]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>-3</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>-2</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>-1</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>-2</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>-1</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>2</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>0</td>
<td>0.9999 0.0001</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0</td>
<td>0.9         0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>0</td>
<td>0.9999 0.0001</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td>0</td>
<td>0.9         0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>0</td>
<td>0.9999 0.0001</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>0</td>
<td>0.9         0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>0</td>
<td>0.9         0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>21</td>
<td>0</td>
<td>0.9999 0.0001</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td>0</td>
<td>0.9         0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>0</td>
<td>0.9         0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>0</td>
<td>0.9         0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>0</td>
<td>0.9999 0.0001</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>26</td>
<td>0</td>
<td>0.9996 0.0001</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
</tbody>
</table>

\[ \tau = 0.1 \quad \tau = 10 \]

Kama et al. (2009)
The “puffed-up” inner rim model

Dullemond, Dominick & Natta (2001)
Isella & Natta (2005)
Vinkovic et al. (2006)
Tannirkulam et al. (2007)
Kama et al. (2009)

MULTI SIZE DUST GRAINS + SETTLING, NEGLIGIBLE GAS OPACITY

Andrea Isella :: Ten years of VLTI: from first fringes to core science :: Garching, October 24th
Observations the "puffed up" inner rim

Akeson et al. (2005)
Isella et al. (2006)
Monnier et al. (2006)
Tatulli et al. (2007, VLTI/AMBER)
Isella et al. (2008, VLTI/AMBER)
Krauss et al. (2008, VLTI/AMBER)
Benisty et al. (2010, 2011, VLTI/AMBER)

Andrea Isella :: Ten years of VLTI :: Garching, October 24th
The rim is not enough

A full treatment of the dust and gas opacity is needed!

Isella et al. (2008)
see also Akeson et al. (2005)

Benisty et al. (2010)
The gaseous inner disk

Kraus et al. (2008)

Muzerolle et al. 2004

Andrea Isella :: Ten years of VLTI: from first fringes to core science :: Garching, October 24th
The gaseous inner disk

Millan-Gabet et al. (PPV)

Strong accretors (e.g. MWC 297, Malbet et al. 2007)
Probing the gaseous inner disk with spectro-interferometry

Overtone CO emission ($V=2-0$) observed with AMBER/Medium Resolution toward 51 Oph (B9, $M_{acc}=10^{-7}$ $M_{sun}/yr$)

Fig. 1. AMBER calibrated spectrum of 51 Oph around the 2-0 and 3-1 bands of the CO overtone at 2.3 microns. For comparison purposes is plotted (dashed line) the same spectrum measured with the TNG spectrograph (L. Testi, private communication). Note that we did not plot the TNG spectrum between the two bandheads because of irrelevant instrumental artifact.

Tatulli et al. (2008)
Magnetospheric accretion

From $R_*$ to a few $R_*$ (< 0.1 AU): ::: <1 mas resolution

Measured from the UV veiling and the Hα line profile (e.g. Muzerolle et al. 2004), but also from infrared H lines such as Brγ and Phβ

Calvet et al. (2004)
Natta et al. (2004)
Bry: accretion or outflow?

Malbet et al. (2007)
Tatulli et al. (2007)
Kraus et al. (2008)

Eisner et al. (2010)

Andrea Isella :: Ten years of VLTI: from first fringes to core science :: Garching, October 24th
Conclusions & Final remarks

- planet formation and planet-disk interaction
- dust evolution, formation and composition of meteorites and comets
- dust sublimation (effects the global disk structure, the formation and migration of planets)
- disk-star connection, jets and winds (regulate the angular momentum of the disk and star)
- accretion (regulate the final stellar mass, depends on the magnetic field and disk viscosity)