A Brief History of Exocomets

Many thanks to my amazing collaborator, Barry Welsh!

Here Today, Gone Tomorrow
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And then something happens. Tens of millions of years go by. The comet goes around the parent star hundreds of thousands of times. And then the comet feels persistent tugs and begins to fall towards the star. Blast, the snow line. And then there wasn’t.

A Brief History of Exocomets
Once upon a time, there was a comet.
EXOCOMETS: A Brief History

• **Introduction:** Why do we care about small, icy bodies?

• **Detection methods:** Finding planetary systems with comets

• **Building planetary systems with comets:** the astrobiology connection

• **Summary:** Unresolved questions and next steps
EXOCOMETS: Why should we care about them?

- **Comets** are fossil bodies that were there at the time of planet formation.

- **Comets** provide indirect evidence of exoplanets.

- Along with the presence of dust, scattered comets may provide indirect evidence of violent collisional cascades.

- **Comets** (and asteroids) may deliver water and other volatiles to planets.
Three ways of detecting them directly:

1) **Time series spectroscopy**  

2) **Millimeter/Sub-millimeter emission from volatiles**  
   *(Matrás et al. 2017 and many more)*

3) **Transits**  
   *Rappaport et al. 2017*
Method #1: Time-series absorption spectroscopy

Experts: Alain Lecavalier des Etangs, Hervé Beust, Barry Welsh, Flavian Kiefer, Daniela Iglesias, Paul Wilson, Vincent Bourrier, Isabel Rebollido Vázquez, Siyi Xu, Sharon Montgomery
Time-series spectroscopy: Beta Pictoris

- Edge-on debris disk imaged in the far-red by Smith & Terrile, 1984
- Ground-based spectroscopy towards Beta Pictoris revealed substantial variation of the circumstellar CaII K-line (3934 Å) on timescales of days and hours. (Ferlet et al. 1987)
- Specifically, the stable, circumstellar absorption at the radial velocity of the star is accompanied by weaker, short-lived absorption at mostly red-shifted velocities.
- This gas transits only a few stellar radii in front of the star?
- Similar variability was subsequently observed in the ultraviolet (Lagrange et al. 1987).
Beta Pictoris: The Exocomet (or FEB) Model

Thébault & Beust 2001
Modeling of the Exocomet Event
(adapted from Beust et al. 1990)
Modeling of the Exocomet Event
(adapted from Beust et al. 1990)

(time = 1.5 hours)
Modeling of the Exocomet Event
(adapted from Beust et al. 1990)

(time = 3 hours)
Modeling of the Exocomet Event
(adapted from Beust et al. 1990)

(time = 4.5 hours)
Modeling of the Exocomet Event
(adapted from Beust et al. 1990)

(time = 6 hours)
Beta Pictoris: Two families of comets
Kiefer et al. 2014

- Statistical analysis of 6000 observations of exocomet events revealed two distinct types of evaporating comets.

- The first family of exocomets (Population S) are old, exhausted comets producing wide, shallow absorptions. These are likely trapped in mean motion resonance with a massive planet.

- The second family of exocomets (Population D) are volatile-rich comets producing narrow, deep absorptions. Sharing similar orbits, these are probably associated with the recent fragmentation of one or more parent bodies.
Similar exocomet activity has now been detected towards a total of 24 stars. See handout!

<table>
<thead>
<tr>
<th>No.</th>
<th>Sp. Type</th>
<th>Reference</th>
<th>Age</th>
<th>Gas emission</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A6V</td>
<td>Ferlet et al. (1997)</td>
<td>23 Myr</td>
<td>CO, CI, CII, OII</td>
<td>var. FeII &amp; CaII triplet, UV, Resolved clumpy CO &amp; CII</td>
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<tr>
<td>2</td>
<td>A2IV/V</td>
<td>Lagrange-Henri et al. (1990)</td>
<td>1.8 Myr</td>
<td>-</td>
<td>-</td>
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<tr>
<td>3</td>
<td>A1IVn</td>
<td>Welsh et al. (1998)</td>
<td>-</td>
<td>-</td>
<td>Shell star, no mid IR excess, variability in NaID reported</td>
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<tr>
<td>4</td>
<td>A1V</td>
<td>Montgomery &amp; Welsh (2012)</td>
<td>40 Myr</td>
<td>CO, C I, C II</td>
<td>NaID variability also reported</td>
</tr>
<tr>
<td>5</td>
<td>A0V</td>
<td>Montgomery &amp; Welsh (2012)</td>
<td>200 Myr</td>
<td>-</td>
<td>Variable in uv, overabundance of carbon</td>
</tr>
<tr>
<td>6</td>
<td>A3Vn</td>
<td>Montgomery &amp; Welsh (2012)</td>
<td>-</td>
<td>-</td>
<td>Cluster star</td>
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<tr>
<td>7</td>
<td>A0V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>80 Myr</td>
<td>-</td>
<td>Eclipsing binary</td>
</tr>
<tr>
<td>8</td>
<td>A3Vn</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>150 Myr</td>
<td>-</td>
<td>Shell star, no mid IR excess</td>
</tr>
<tr>
<td>9</td>
<td>B9V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>90 Myr</td>
<td>-</td>
<td>δ Scuti &amp; λ Boo star, Herschel Image</td>
</tr>
<tr>
<td>10</td>
<td>A2V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>5 Myr</td>
<td>-</td>
<td>Weak λ Boo, no mid IR excess</td>
</tr>
<tr>
<td>11</td>
<td>A7V</td>
<td>Kiefer et al. (2014)</td>
<td>23 Myr</td>
<td>O I</td>
<td>Variable in uv, polarimetry observations of hot disk</td>
</tr>
<tr>
<td>12</td>
<td>A6V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>550 Myr</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>B9V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>60 Myr</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>14</td>
<td>A3V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>4 Myr</td>
<td>-</td>
<td>-</td>
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<tr>
<td>15</td>
<td>A0V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>500 Myr</td>
<td>-</td>
<td>-</td>
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<tr>
<td>16</td>
<td>A0V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>750 Myr</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>17</td>
<td>A0V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>1000 Myr</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>A0V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>1500 Myr</td>
<td>-</td>
<td>-</td>
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<tr>
<td>19</td>
<td>A0V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>2000 Myr</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>A0V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>2500 Myr</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>21</td>
<td>A0V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>3000 Myr</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>22</td>
<td>A0V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>3500 Myr</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>23</td>
<td>A0V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>4000 Myr</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>24</td>
<td>A0V</td>
<td>Welsh &amp; Montgomery (2013)</td>
<td>4500 Myr</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Approximately 40 other A-stars showed no variation over 3-4 nights.
Studies at other wavelengths

- **For Beta Pictoris and HD 183324 only:** Variability at the CaII K-line (3934Å) is occasionally accompanied by weak absorption variability at FeI 3860Å, usually at similar red-shifted velocities. (Welsh & Montgomery, 2016 & 2017)

**Beta Pictoris**
Example of simultaneous absorption by ionized calcium and neutral iron at similar redshifts.
**Studies at other wavelengths**

- **Beta Pictoris and HD 183324** also show circumstellar variability at the CaII triplet at 8542Å.

- Three of these stars (*Beta Pic, 49 Ceti, HD 172555*) show similar absorption variability in the wings of strong lines (e.g., FeII, MgII, CII, and CIV) in the **ultraviolet** -- indicating transient gas mainly falling toward the central star. (Lagrange et al. 1987; Miles et al. 2016; Grady et al. 2018)
### Puzzlers: An additional six stars

<table>
<thead>
<tr>
<th>Star Name</th>
<th>Alias</th>
<th>Sp. Type</th>
<th>Reference</th>
<th>Age</th>
<th>Gas emission</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 2262</td>
<td></td>
<td>A5Iv</td>
<td>Welsh &amp; Montgomery (2018)</td>
<td>350</td>
<td></td>
<td>Weakly variable but no c/s absorption</td>
</tr>
<tr>
<td>HD 30422</td>
<td></td>
<td>A3V</td>
<td>Welsh &amp; Montgomery (2018)</td>
<td>13 Myr</td>
<td></td>
<td>Weakly variable but no c/s absorption</td>
</tr>
<tr>
<td>HD 45557</td>
<td></td>
<td>A0V</td>
<td>Welsh &amp; Montgomery (2018)</td>
<td>75 Myr</td>
<td></td>
<td>Weakly variable but no c/s absorption, Herschel image</td>
</tr>
<tr>
<td>HD 181296</td>
<td>η Tel</td>
<td>A0V</td>
<td>Welsh &amp; Montgomery (2018)</td>
<td>23 Myr</td>
<td>C II</td>
<td>Weakly variable but no c/s absorption</td>
</tr>
<tr>
<td>HD 188228</td>
<td>ε Pav</td>
<td>A0V</td>
<td>Welsh &amp; Montgomery (2018)</td>
<td>40 Myr</td>
<td></td>
<td>Weakly variable but no c/s absorption, Herschel image</td>
</tr>
<tr>
<td>HD 80007</td>
<td>β Car</td>
<td>A2IV/V</td>
<td>Redfield (2007)</td>
<td>260 Myr</td>
<td></td>
<td>Comet-like variability only at NaID-line</td>
</tr>
</tbody>
</table>
Method #2: Detecting comets by tracing the gas

Experts: Luca Matrà, Alexis Brandeker, Quentin Kral, Inga Kamp, Mihkel Kama, Viviana Guzmán, Ilsa Cleeves, Maria Cavallius, Harold Linnartz, Liton Majumdar, Stephanie Milam
Atacama Large Millimeter/Submillimeter Array (ALMA)
Evidence the gas may come from comets

How is second-generation exocomet gas different from primordial gas?

- **Composition**: e.g., hydrogen should be underabundant
- **Density**: CO should be optically thin
- **Location**: Cometary gases and dust should be co-located
- **Distribution**: CO may be clumpy or otherwise asymmetric
- **Consistent markers**: Models make accurate predictions, transits, etc.

**Four systems with confirmed exocomet gas**: Beta Pictoris, Eta Corvi, Fomalhaut, and HD 181327

**Two additional systems suspected to contain exocomet gas**: 49 Ceti and TWA 7
Multiple belts of debris with different inclinations (Wahhaj et al. 2003, Okamoto et al. 2004). Dust disk beyond 100 AU likely due to collisional cascade. (Quillen et al. 2007)

The disk includes magnesium-rich olivine similar to that found in Solar System comets, which is different from that found in Solar System asteroids (De Vries et al. 2012).
The disk of Beta Pictoris: Where’s the gas?

- **Co-located**: Dust, CO, and CI are located together in a belt about 85 AU from the star.

- **Asymmetry**: The CI and CO are clumpy. (Dent et al. 2015 and Cataldi et al. 2018).
The disk of Beta Pictoris: Composition of the Gas

- **Abundance of Atomic CNO:** The gas is extremely overabundant in carbon (Roberge et al., 2006) and oxygen (Brandeker et al. 2016)..... but the abundance of nitrogen is near solar (Wilson et al. 2019).

- **Abundance of CO:** The CO is underabundant relative to both CI and CII, which is suggestive of an underabundance of hydrogen. Thus this is also consistent with a cometary origin (Higuchi et al. 2017).

- **Abundance of Atomic H:** Wilson et al. (2017) detected atomic hydrogen falling towards the star -- too much to have been released from chondrite meteorites and too little to be primordial.
The disk of 49 Ceti: A Puzzle

- **Composition:** Carbon is extremely overabundant (Roberge et al. 2014).

  But CO was not observed in absorption....

  ...And OI has not been detected in emission.

- Might this mean that the molecular gas is in a thinner disk than the atomic gas? *A thinned disk might suggest an underabundance of molecular hydrogen.*

- **Location & Distribution:** Neither the dust nor the gas show obvious asymmetries and they are not co-located.
The disk of Fomalhaut

- A3V, 440 million years old

- **Co-located** narrow ring of dust and CO. (MacGregor et al. 2017 and Matrà et al. 2017).

- **Amount:** Low. The CO+CO$_2$ mass fraction is consistent with exocometary gas. (Matrà et al. 2017)

- **Asymmetry:** Approximately 50% of the CO flux comes from a region near the belt’s pericenter. (Matrà et al. 2017)
The disk of Fomalhaut

- **Planet:** Fomalhaut b (“Dagon”) is in a 2000-year-long, highly elliptical orbit that crosses the main debris belt. This likely leads to collisions and strong scattering. (Kalas et al. 2008, 2013)

- So where are the infalling comets?
The disk of Eta Corvi:

- F2V, 1400 million years old (old)
- **Cold dust** in a wide belt far from the star.
- **Hot dust** (within 3 AU) that had to have been passed inward.
- CO at 20 AU from star, which is consistent with the release of volatiles from planetesimals as they cross the ice lines.
- **Compelling story:** One or more hidden planets far from the star (around 100 AU) could sculpt the disk, scatter material inward from the cold belt to the hot zone, and these scattered comets could release CO at the ice line (Marino et al. 2017).
Method #3: Detecting comets through transits

Transit experts: Eva Bodman, Vincent Bourrier, Ernst de Mooij, Matthew Kenworthy, Ignas Snellen, Paul Molière

Transiting Exoplanet Survey Satellite 2018
Discovery of Minor Bodies through Transits

- **Sub-Earths:** Smallest solid body detected as of 2017 was moon-sized Kepler 37b (Barclay et al. 2013)

- **Disintegrating planets:** Ceres-sized objects in short period orbits (around 10 hours) detected in transit by virtue of their dusty effluent, for example KIC 1255b (Rappaport et al. 2012)

- **Comets!** 6 asymmetric transits of KIC 3542116 (F2V) and one of KIC 11084727 (F5V) that are consistent with transits by comet tails. (Rappaport et al 2017)

- **Distinctive shape** predicted by Lecavelier des Etangs et al (1999)!
**Comets:** And one more system makes three!

**Beta Pictoris:** Zieba, Zwintz, Kenworthy & Kennedy, 2019 (accepted to A&A)
Tabby’s Star: Transit by a swarm of comets?

- **Comet swarms?** Although not especially comet shaped, the deep (22%), long (5-50 days) dips in the flux of KIC 8462852 may be due to swarms of very large comets (Boyajian et al. 2016). See also Bodman & Quillen, (2016).

- **Two smaller transits of similar shape:** Kiefer et al. 2017 find two scenarios consistent with the light curves.

  **Scenario #1:** The star is occulted by a string of about six comets at a distance of 0.3 AU.

  **Scenario #2:** The star is occulted by a planet with a wide ring system.
Astrobiology Connection: Scattering Comets to the Habitable Zone

Experts on modeling planetary systems: Birgit Loibnegger, Hervé Beust, Nader Haghighipor, Kateryna Frantseva, Hilke Schlichting, Santiago Torres
Astrobiology connection: Scattering comets to the Habitable Zone and enabling life

**Step 1:** Build a terrestrial planet in the habitable zone

**Step 2:** Scatter comets into the habitable zone

**Step 3:** Direct many water-rich comets to impact the terrestrial planet.

Experts on Astrochemistry & Astrobiology who will handle Steps 4-99:
Clara Sousa-Silva, Jennifer Bergner, Kimberly Bott, Herman Cuppen, Jana Hncirová, John Harrison, Liton Majumdar, Ferus Martin, Stefanie Milam, Paul Molière, Paul Rimmer, Sarah Rugheimer, Tajana Schneiderman, Zoe Todd
The fate of scattered objects

How to design a planetary system (Wyatt et al. 2017)

Land of Eventual Accretion

Land of Eventual Ejection

Now (4.5 Gyr)

Past

Future

Planet mass (in Earth-masses)

Semi-major axis (in AU)
The fate of scattered objects

- **Ejected**
- **Remaining**
- **Accreted**

- **Semi-major axis (in AU)**
- **Planet mass (in Earth-masses)**

- **1M⊙**

- **ESCAPING**
- **DEPLETED OORT CLOUD**
- **DEPOSITED IN OORT CLOUD**
- **NOW**
The fate of scattered objects

- **Accreted**
- **Ejected**
- **Remaining**

- ESCAPING
- DEPLETED OORT CLOUD
- DEPOSITED IN OORT CLOUD

**Semi-major axis (in AU)**

**Planet mass (in Earth-masses)**

- 1M_
- 10M_
- 100M_
- 1000M_
- 10000M_

- JV
- ME
- UN
- VM
- MM

- 1
- 10
- 100
- 1000
- 10000

- 0.1
- 1
- 10
- 100
- 1000

- 0.01
The fate of scattered objects

Chain of planets, all within this region of parameter space will maximize inward scattering.
The fate of scattered objects

- **Accreted**
  - Known Hot Jupiters
  - Known Super Earths
  - Eccentric Jupiters

- **Ejected**
  - Long-Period Giants

- **Remaining**

**Planet mass (in Earth-masses)**

**Semi-major axis (in AU)**
EXOCOMETS: Building planetary systems with comets
Systems that fit these criteria should be investigated first

To maximize the influx of comets and the delivery of volatiles: (Wyatt et al. 2017)

1) A chain of closely-spaced planets far from the star (see also Bonsor & Wyatt, 2012)
2) No ejectors
3) An accretor in the Habitable Zone
4) A mechanism (e.g., migrating planets, resonance) for replenishing infalling comets

![Diagram showing the fate of scattered objects with labels for ejected, accreted, and remaining objects on a log-log scale.](image-url)
EXOCOMETS: Unresolved questions

- Why is Beta Pictoris so unusual? Why are there so few exocomet systems with measurable absorption at FeI (3860Å) or the CaII triplet (8540Å)?

- Might some of the transient absorptions we observe in A-stars be due to something other than infalling comets (e.g., a stellar phenomenon or infalling circumstellar gas)?

- Has the regular in-fall of cometary material onto the stellar surface changed the stars’ metallicities?

- Why don’t we see interstellar-like molecules in exocomet spectra? Where is the CH, CH⁺,....?

- How is water transported to the inner rocky worlds? Are scattered comets important?
EXOCOMETS: Next steps

• Collaborate to make synchronous observations.

• Observe more stars in the ultraviolet so as to inventory the infalling gas.

• Inventory the gas in a large population exocometary belts. Include in this inventory those agents that are crucial for the synthesis of the building blocks of life and reactive nutrients.

• Advocate for a far infrared detector that is sensitive to water and OH (e.g., ORIGINS).

• Relate the exocomet work to the astrobiology and chemistry models of planets and planetary atmospheres.