EXOCOMETS WITHIN PLANETESIMAL BELTS

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Comets carry complex volatiles e.g. amino acid glycine (Wild/2, 67P), and simple feedstock molecules needed for prebiotic chemistry.

Geochemical and dynamical evidence for heterogeneous accretion of Earth

Water-dominated bodies arrive late during Earth’s accretion, when Solar System was ~10s of Myr old

Originated in our Solar planetesimal belt, the Kuiper and Asteroid belts.

WHY EXOCOMETARY SCIENCE

- Solar System comet composition only observable near the Earth - thermal processing
- Observed at 4.6 Gyr - irradiation, collisional evolution
- Few data points - and lots of scatter, sign of different evolutions?
- What we would really like to know is their composition and dynamics during the epoch of volatile delivery, in the terrestrial planet formation era at 10s-100 Myr.

Mumma & Charnley 2011, Guilbert-Lepoutre+ 2015
EXTRASOLAR BELTS

But:

- At least ~20% of main sequence stars are surrounded by belts of IR-emitting dust.
- Dust is short lived due to radiation pressure -> it must be continuously produced.
- Large bodies are producing observable dust in a collisional cascade.

Sepulveda et al. 2019

\[ F_{v, \text{star}} \quad F_{v, \text{disk}} \]

\[ L_{\star} \quad L_{\text{IR}} \]

200 AU

e.g. Matthews+ 2014, Backman+ 1993, Wyatt+ 2002
COLLISIONAL EVOLUTION

- Belt loses mass over time (as observed)
- Mass loss rate faster at shorter radii (higher velocities)
- Biased towards brighter belts that are young, and have large radii (far from the star)

Observe icy exocomets in 10-few 100 Myr period when inward delivery is most likely taking place
After protoplanetary disk dissipation:

- Exocomets in belt(s)
- Exocometary dust (debris)
- Star
- Planet(s)
EXOCOMETS

Gas released through collisional cascade by exocomets within belt

Time-variable redshifted gas and dust released by inward-scattered exocomets

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**UV/optical absorption**

\[ \text{Incoming Flux} \]

\[ V_{\text{star}} + V_{\text{proj}} \]

\[ V_{\text{ISM}} \]

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**Millimeter / far-IR emission**

\[ \text{Incoming Flux} \]

\[ V_{\text{star}} \]

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**Broadband transits**

\[ \text{Incoming Flux} \]

\[ t_{\text{transit}} \]

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**Keplerian disk**

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**To Earth**
CO IN EXOCOMETARY BELTS

• Now detected in the majority (18) of belts observed by ALMA

β Pictoris

HD 21997

Dust

50 AU

C^{18}O

50 AU

Kospal+2013, Dent+2014, Matrà+ 2017a and in prep
CO in EXOCOMETARY BELTS

- Pushing to the limit of detectability with ALMA: $10^{-6/-7}$ Earth masses.
THE CASE FOR EXOCOMETARY GAS

• Just like the dust, it’s a matter of timescales

• Too little CO (and likely unseen H2) to shield CO -> cannot survive against photodissociation over the system’s lifetime.

CO must be replenished through exocometary outgassing, so it is second-generation like the dust

β Pictoris

CO J=2-1

THE GAS RELEASE MODEL

- Collisional cascade is in place and is losing solid mass via gas release and ejection of small grains.

\[ M_{\text{Dmax}} = M_{\text{CO}} + M_{\text{Dmin}} \]

but also

\[ M_{\text{CO}} = M_{\text{Dmax}} f_{\text{CO}} \]

- \( M_{\text{CO}} \) and \( M_{\text{Dmin}} \) can be estimated from observations

Matrà+ 2015, 2017b, Marino+ 2016, Kral+ 2017
How do they compare with solar system comets?

Consistent with one another, but need more (and more accurate) comet and exocomet observations.

Advantage: Probe entire exocometary reservoir.

CO is the only molecule detected so far in exocometary belts. What about other molecular species?
Beta Pic is an active A star, strong UV flux

Most cometary molecules destroyed much faster than CO

Makes sense that it’s all we have detected

CN is the next most promising target

CN is a daughter molecule, produced mostly by photodissociation of HCN

Matrà+ 2018a
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RESULT: LOW HCN/CO OUTGASSING RATIO

- At the low end of Solar System comets as observed at ~1 AU

Is low value due to ice abundance depletion or to the outgassing mechanism?

Cometary abundances from Le Roy+ 2015, Womack+ 2017
**THE DOMINANCE OF ATOMIC GAS**

- Molecular gas produces atoms which dominate the gas abundance.

- Atomic gas will viscously spread radially to produce an accretion disk in a viscous timescale.

- If gas production rate high enough, enough C can accumulate to shield CO and allow it to pile-up too!

  Produces very CO-rich *shielded* exocometary belts.

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Kral+2016, Cataldi+2014, Brandeker+2016, Higuchi et al. 2017
NO ACCRETION DISKS?

- Despite low resolution, C I appears co-located with CO radially

- Low viscosity, long spreading timescale

- Something prevents atomic gas from spreading inwards: Radiation pressure? Planets?

- Very recent onset of gas production

Cataldi et al. 2018, 2019, Kral et al. 2018
WHY EARLY TYPE STARS?

CO mass released through collisional cascade for a given planetesimal belt:

\[ M_{\text{CO}} = 1.2 \times 10^{-3} R^{1.5} \Delta R^{-1} f^2 L_{\star} M_{\star}^{-0.5} t_{\text{phd}} \frac{f_{\text{CO+CO}_2}}{1 - f_{\text{CO+CO}_2}} \]

Dependence on stellar luminosity: observed, more luminous stars have belts with higher mass loss rates

Finally have an M star! **TWA 7**
SUMMARY

Why exocomets?
Probes dynamics and composition of planetary systems at the volatile delivery epoch, when exocomets may deliver key species for prebiotic chemistry to inner rocky planets.

Evidence for exocomets

**Inward-scattered populations** from
1. Time-variable red/blue-shifted gas absorption
2. Broadband transits from ‘shark-fin’ dust tails
3. Exozodiacal warm/hot dust piling up close to the star

**Outer exocometary belts** from
4. Stable gas absorption at the stellar velocity
5. Cold (sub-)millimeter molecular and atomic gas emission

The millimeter perspective
1. CO is ubiquitous - detected in the majority of belts observed by ALMA
2. Molecular gas has to be exocometary in at least some systems because of short survival timescale
3. Gas released within collisional cascade -> CO ice mass fractions ~consistent with Solar System
4. Atomic gas dominates the mass and expected to viscously spread
5. A stars dominate CO detections due to higher mass loss rates combined with detection bias