Debris discs, exoasteroids and exocomets

Mark Wyatt
Institute of Astronomy, University of Cambridge
The Sun has belts of planetesimal debris at ~40au and 2-3au that collide and fragment into dust observable from Earth as the zodiacal cloud.
Some nearby stars have outer and inner debris

η Corvi is a nearby 18pc ~1Gyr main sequence F2 star exhibiting dust emission at a two-temperatures, from two belts

Cold dust at 152au (Wyatt+05; Duchene+14; Marino+17)

Hot dust at ~0.7au (Smith+09; Lisse+12; Defrere+14)
Luminosities and radii of exo-Kuiper belts

Herschel DEBRIS+DUNES survey of nearest 273 Sun-like (FGK) stars

20% of stars have belts with fractional luminosity $\sim 10^{-5}$ at radii $\sim 40$au

These are 100x brighter than our Kuiper belt (Vitense et al. 2014), and so didn’t undergo depletion

See Booth talk
Masses of exo-Kuiper belts

Total mass in mm-sized dust is much lower than in protoplanetary disks, and is comparable to the Moon.

But collisions erode Kuiper belts over time, and if this is all there was the disks would disappear rapidly.

Infer planetesimals at least 10s of km in size and total mass of 10s of $M_{\text{earth}}$.

Decrease in disk luminosity with age in disk population also explained by collisional erosion.
Gas content of exo-Kuiper belts

ALMA is revolutionising our understanding of gas in debris disks. Not only do ~10-40Myr disks have gas, but also old stars (all stars?). Eg, 440Myr Fomalhaut has $0.7-40 \times 10^{-7} M_{\text{earth}}$ of CO (ie, one comet) in belt.

Matra et al. (2017)

MacGregor et al. (2017)
Composition of exo-Kuiper belts

Detection of CO implies origin in volatile rich planetesimals

Know mass loss rate of solids (from dust) and of CO (lasts \(\sim 120\) yr); if steady state, know volatile fraction

Also dust features, eg, 4\% of \(\beta\) Pic dust is forsterite (de Vries et al. 2012)

Implies similar composition to comets in Solar System

So if planetesimals are scattered in and collide with planets, volatile delivery likely
Old asteroid belts must be faint

To assess if exocomets are scattered in, look for hot exozodiacal dust.

Collisional erosion means that close-in belts quickly drop below detection threshold, with a max fractional luminosity (Wyatt et al. 2007):

\[ f_{\text{max}} \sim 0.16 \times 10^{-3} r^{7/3} t^{-1} \]

So, consider hot dust at 12µm to exclude possibility of asteroid belt emission.
Hot (~1au) dust around nearby stars

The 150au belt of η Corvi has hot dust closer in at ~1au with spectrum matching comet dust (Lisse et al. 2012)

The 400K mid-IR spectrum of 2Gyr HD69830 suggests dust at ~1au with no outer belt (Beichman et al. 2005, 2011; Smith et al. 2009)

Just outside 3 Neptune mass planets discovered in radial velocity studies (Lovis et al. 2006)
Is dust brought in by PR drag?

Dust distribution inside planetesimal belt due to PR drag and mutual collisions depends on (Wyatt 2005)
\[ \eta_0 = \frac{t_{pr}}{t_{col}} = 10^4 \tau_{\text{eff}} (r/M_\star)^{0.5} \]

For detectable disks, these must be dense enough for \( \eta_0 > 1 \) (Wyatt et al. 2007)

But some dust makes it in at level independent of outer belt density:
\[ \tau_{\text{max}} = 2.5 \times 10^{-5} \ (M_\star/r)^{1/2} \] (see also van Lieshout et al. 2014)  
See Lohne talk
Mid-IR emission from dragged in dust is detectable

Model predicts 0.1-1% mid-IR excesses, agreeing with KIN 8.5µm detections for 5/20 stars with outer Kuiper belts (Mennesson et al. 2014)

Model predictions can be improved (van Lieshout et al. 2014); maybe enhance dust by resonant trapping (Shannon et al. 2015), or deplete by scattering (Moro-Martin & Malhotra 2005; Kennedy & Piette 2015)

Low levels of hot emission explained (inevitable) without impactors, but bright dust like η Corvi still unexplained
Detection of CO to η Corvi at ~22au!

ALMA observations also used to search for CO: none in 150au ring... but CO detected at ~20au! Sublimation of icy comets passing a CO$_2$ (?) snow-line would explain this as ~88K (Marino et al. 2017)

Loss rate is high (but not unreasonable) at ~3M$_{\text{earth}}$/Gyr and similar to that of hot dust (Wyatt et al. 2010)
Late Heavy Bombardment (LHB)

LHB epoch has maximum comet influx; explains unusual hot dust to η Corvi?

Mid-LHB distribution in Nice model (Gomes et al. 2005) is:
• asymmetric (Pearce & Wyatt 2015)
• broad (Booth et al. 2009)

Too broad to fit η Corvi (Marino et al. 2017)
Scattering outcomes for Sun-like stars

Consider planetesimals being scattered by planet with $M_{pl}$, $a_{pl}$

Five main possible outcomes: accreted, ejected, remaining, Oort Cloud, escaping

Wyatt et al. (2017)
Implications of these outcomes

Many systems have ejectors that act as barrier to comets.

Young systems can have population of escaping embryos / scattered disk.

Oort Clouds generally inefficient and 10,000au (Tremaine 1993).

Embedded planets can take Gyr to deplete disk, providing ongoing replenishment of comets.

Planets above $v_{esc} = v_k$ line didn't grow by impacts.

Giant impacts expected during formation release debris that persists for Myr-Gyr.

$1 M_{sun}, 4.5 \text{Gyr}, 0.1 M_{sun}/pc^3$
Maximising exocomets

More complicated, as likely multiple planets, but three main principles:

• Chain of planets, with no ejector

• Planets not increasing $M_{pl}$ with $a_{pl}$

• Replenishment, possibly from embedded low-mass planet
Summary of planets orbiting η Corvi?

Current planet detection thresholds up here (Borgniet et al. 2016)

- Collides with planet to create hot dust?
- Planet truncating disk inner edge
- Chain of planets passing planetesimals inward

If planets orbit inside other exo-Kuiper belts, these systems should also have exo-comets at a level dependent on planet architecture
FEBs are thought to be planetesimals originating in a 4au asteroid belt, perturbed onto star crossing orbits by inner mean motion resonances with $\beta$ Pic-b at 9au (Beust & Morbidelli 2000). See Rebollido talk and Welsh poster.

This mechanism may be more widely relevant (Faramaz et al. 2017; Pichierri et al. 2017).
Exo-asteroid belts

Emission spectrum of several stars shows two temperature components (Chen et al. 2006; Kennedy & Wyatt 2014)

The hot dust is typically ~3x hotter, so could be an exo-asteroid belt ~9x closer in than the exo-Kuiper belt

But this emission could also come from exo-comets, or dust dragged in by PR drag AND we can still only detect dust levels >1000x zodiacal dust levels
How common is faint inner dust?

Already direct imaging of bright asteroid belts (Su et al. 2017) Nulling mid-IR interferometry will detect <few% excesses

HOSTS: NASA-funded project (PI: Phil Hinz) using LBTI to search ~60 of the nearest stars for 11µm emission from inner dust approaching 10x zodiacal cloud

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<table>
<thead>
<tr>
<th>R12 = F_disk/F_star at 12µm</th>
<th>Fraction &gt; F_disk/F_star at 12µm</th>
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</thead>
<tbody>
<tr>
<td>Solar System level</td>
<td>~Solar System level</td>
</tr>
<tr>
<td>exo-Earth imaging limit</td>
<td>~exo-Earth imaging limit</td>
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<tr>
<td>LBTI limit</td>
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<td>WISE limit</td>
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HD69830 and η Corvi
Giant impacts?
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Giant impact debris

Expect giant impacts in final stages of terrestrial planet formation, and large 12μm excesses seen for ~3% of young (<100Myr) stars

Spectrum of 23Myr HD172555 shows dust composition dominated by silica suggesting origin in >10km/s collision (Lisse et al. 2009)
Detectability of Earth-Moon impact debris

Roughly a Moon mass of debris is expected to escape in impact 30Myr to remove dynamically (re-accretion onto planets), but also collisionally depletes (Jackson & Wyatt 2012)

Detectability depends on size distribution and assumptions of optical properties etc (Wyatt & Jackson 2016)

~30% of mass is vaporised and condenses into ~1cm grains (Johnson & Melosh 2014) which have a bright excess that decays quickly

Larger debris ( rubble up to 500km?) is fainter but possibly still detectable for 10s of Myr

See Bottke talk
Duration of detectability of giant impact debris

Assume 5% of $M_{\text{pl}}$ released in GI, size distribution, strength, emissivity of debris

Account for reaccretion onto planet, collisional erosion of debris

How long debris lasts above 12µm detection threshold $R_{12} = F_{\text{dust}}/F_*$

Debris lasts longest and so is most readily detectable for these planets

If GI occur with equal probability per $[\log(M_{\text{pl}}), \log(a_{\text{pl}})]$ this is where first GI detected
Where is GI debris seen?

Star with proposed GI debris ($R_{12} > 0.1$)

Expected GI detection locations for these stars if GI occur with equal frequency in $\log(M_{pl})$, $\log(a_{pl})$ bins

Why few FGK giant impacts at 1-3au: No planets there? Detection bias?
Conclusions

• 20% of stars have massive Kuiper belt likely comprised of icy comet-like bodies (Matra et al. 2017)

• For η Corvi these comets are likely scattered in where they sublimate and potentially collide with a planet (Marino et al. 2017)

• Same likely true for other systems, but depends on planetary system (Wyatt et al. 2017)

• Hot dust for some stars probably evidence of exo-asteroid belts, but need to disentangle signal from dragged in dust and exo-comets (LBTI)

• Also, evidence for giant impacts around <100Myr stars, since dust should remain detectable for O(Myr) (Wyatt & Jackson 2016)