LETTER

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Comet-like mineralogy of olivine crystals in an extrasolar proto-Kuiper belt

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Some planetary systems harbour debris disks containing planetesimals such as asteroids and comets[1]. Collisions between such bodies produce small dust particles[2], the spectral features of which reveal their composition and, hence, that of their parent bodies. A measurement of the composition of olivine crystals ($Mg_{2-2x}Fe_{2x}SiO_4$) has been done for the protoplanetary disk HD 100546 (refs 3, 4) and for olivine crystals in the warm inner parts of planetary systems. The latter compares well with the iron-rich olivine in asteroids[5,6] ($x \approx 0.29$). In the cold outskirts of the β Pictoris system, an analogue to the young Solar System, olivine crystals were detected[7] but their composition remained undetermined, leaving unknown how the composition of the bulk of Solar System cometary olivine grains compares with that of extrasolar comets[8,9]. Here we report the detection of the 69-micrometre-wavelength band of olivine crystals in the spectrum of β Pictoris. Because the disk is optically thin, we can associate the crystals with an extrasolar proto-Kuiper belt a distance of 15–45 astronomical units from the star (one astronomical unit is the Sun–Earth distance), determine their magnesium-rich composition ($x = 0.01 \pm 0.001$) and show that they make up 3.6 ± 1.0 per cent of the total dust mass. These values are strikingly similar to those for the dust emitted by the most primitive comets in the Solar System[8–10], even though β Pictoris is more massive and more luminous and has a different planetary system architecture.

The olivine crystals found in the Itokawa asteroid and in ordinary chondrites (types 4 to 6) have an iron-rich composition[5] ($x \approx 0.29$). In contrast, laboratory measurements of olivine crystals from unequilibrated bodies such as comet 81P/Wild 2 and cometary interplanetary dust particles show that these crystals have a range of compositions, but the distribution has a pronounced and sharp peak at the almost-pure magnesium-rich composition with $x \approx 0.01$ (refs 8, 9). Both laboratory experiments[11] and observations[3,4] show that crystal formation in protoplanetary disks by gas-phase condensation, thermal annealing and shock heating results in magnesium-rich crystalline olivine[12–16] ($x < 0.1$). During the protoplanetary disk phase, these olivine crystals are incorporated into planetesimals. An example of a planetary system in which the olivine crystals are then freed from such planetesimals by collisions is the system of β Pictoris. This system is a young (~12 Myr) analogue to the Solar System, with at least one planet at a distance of ~10 AU and a dusty debris disk containing small dust grains[7,17–20] (Fig. 1).

We have detected (Fig. 1) the 69-μm spectral band of small (~2-μm; see Supplementary Information), crystalline olivine grains in the planetary system of β Pictoris using Herschel[21] PACS[22]. The 69-μm band is of special interest because its exact peak wavelength and width are sensitive to both the grain temperature and, in particular, the composition of the olivine crystals[23,24] (Fig. 2). From our model fitting of the 69-μm band and spectral bands at shorter wavelengths (Fig. 1), the temperature and total mass of the crystals are determined

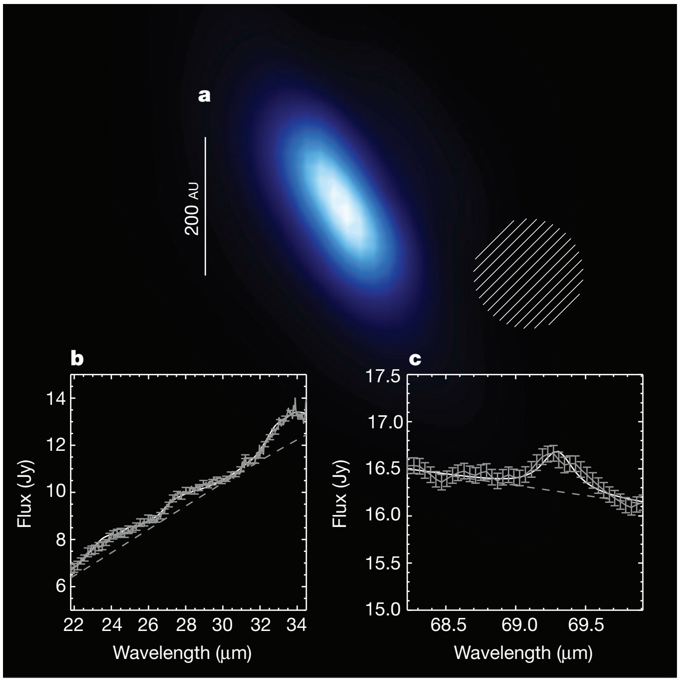

Figure 1 | Photometric and spectral observations of the planetary system of β Pictoris. **a**, Resolved surface brightness map of the β Pictoris debris disk at 70 μm taken with the Herschel Space Observatory's[21] Photodetector Array Camera and Spectrometer[22] (PACS). The disk is barely resolved with PACS, which has a point-spread function with a full-width at half-maximum of 8.2″ (hatched circle). **b**, Spitzer Space Telescope infrared spectrograph spectrum showing prominent olivine features[7] (solid grey). The white solid line is our best model fit and the grey dashed line is the continuum. The uncertainties (1σ) in the Spitzer data[7] are indicated in the figure. **c**, The flux-corrected PACS spectrum with error bars (1σ) showing the 69-μm band of crystalline olivine (solid grey; 12σ detection). The white solid line shows the model fit to the 69-μm band of crystalline olivine as described in Supplementary Information, and the dashed grey line shows the underlying dust continuum. The best model contains crystalline olivine ($Mg_{2-2x}Fe_{2x}SiO_4$) with $x = 0.01 \pm 0.001$ (1σ) and a temperature of 85 ± 6 K (1σ).

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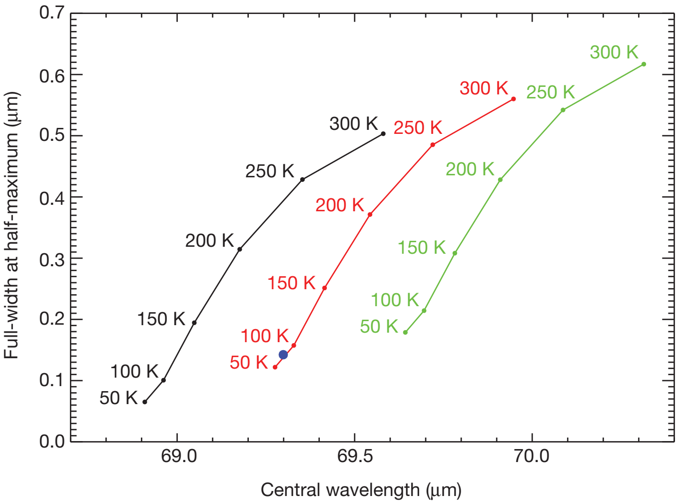

Figure 2 | Diagram demonstrating the dependence of the 69-μm band on grain temperature and composition. The diagram gives the width and central wavelength of the 69-μm band for six temperatures and for crystalline olivine ($Mg_{2-2x}Fe_{2x}SiO_4$) with $x = 0.0$ (black), $x = 0.01$ (red) and $x = 0.02$ (green). The width and central wavelength are measured by fitting Lorentzian profiles to laboratory measurements[23,24] of crystalline olivine at different temperatures and compositions (see Supplementary Information for additional information). The width and wavelength positions measured show how the band broadens and shifts as a function of temperature or iron content. The best model fit of the 69-μm band of β Pictoris is indicated with a solid blue dot (Fig. 1b, c, white solid line); that is, the olivine crystals are cold (85 ± 6 K) and contain about 1% iron ($x = 0.01 \pm 0.001$).

to be 85 ± 6 K and $(2.8 \pm 0.8) \times 10^{23}$ g, respectively. The exact wavelength position of the 69-μm band indicates very magnesium-rich crystalline olivine ($x = 0.01 \pm 0.001$ (1σ)). The fraction of olivine crystals to the total amount of dust (obtained from the spectral energy distribution; see Supplementary Information) is 3.6 ± 1.0% (1σ). The temperature of 85 ± 6 K (1σ) places the population of olivine crystals between 15 and 45 AU from the central star, which coincides with a strong increase in surface density in the disk[25]. This location is outside the snow line of the system, where icy, comet-like bodies can exist, such as in the Kuiper belt of the Solar System. Scaling the distances in the β Pictoris system to those of the Solar System according to the different luminosities of the two central stars, the extrasolar Kuiper belt of β Pictoris reaches into the temperature range of the Jupiter–Saturn region. We propose that this location is an inward extension of what will in time become an analogue of the Kuiper belt of the Solar System.

The composition of the olivine crystals around β Pictoris is strikingly similar to that found in cometary bodies in the Solar System. From the low iron content, we can conclude that the olivine crystals we observe in β Pictoris come from collisions between unequilibrated, relatively small (<10-km) comet-like bodies[5]. The magnesium-rich olivine crystals around β Pictoris are in stark contrast to the iron-rich crystalline olivine[5] ($x = 0.29$) found in asteroid-like bodies in the Solar System. When we compare the crystalline olivine abundance found in β Pictoris (3.6 ± 1.0%) to that of primitive comets in the Solar System, similar low values are found. The comets 17P/Holmes and 73P/Schwassmann–Wachmann, for example, contain about ~2–10% crystalline olivine compared with the total amount of dust[10,26,27]. Because olivine crystals can be formed only within 10 AU of the central star[12–15] there must have been a transportation mechanism to bring these crystals to Kuiper belt distances. Studies of crystalline material and gas have indeed shown that radial mixing has taken place in both the Solar System and disks around young stars[28,29]. Models are able to predict crystalline olivine abundances of 2–58% at radii beyond 10 AU on timescales of ~1 Myr (refs 12, 30). The similar crystalline olivine abundances in β Pictoris and Solar System comets suggest that radial mixing must have been at work during the formation of the β Pictoris planetary system, with an efficiency similar to that in the protosolar nebula.

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