

A dynamical calibration of the mass–luminosity relation at very low stellar masses and young ages

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Mass is the most fundamental parameter of a star, yet it is also one of the most difficult to measure directly. In general, astronomers estimate stellar masses by determining the luminosity and using the ‘mass–luminosity’ relationship^{1,2}, but this relationship has never been accurately calibrated for young, low-mass stars and brown dwarfs³. Masses for these low-mass objects are therefore constrained only by theoretical models^{1,2}. A new high-contrast adaptive optics camera^{4–6} enabled the discovery of a young (50 million years) companion only 0.156 arcseconds (2.3 AU) from the more luminous (>120 times brighter) star AB Doradus A. Here we report a dynamical

determination of the mass of the newly resolved low-mass companion AB Dor C, whose mass is 0.090 ± 0.005 solar masses. Given its measured 1–2-micrometre luminosity, we have found that the standard mass–luminosity relations^{1,2} overestimate the near-infrared luminosity of such objects by about a factor of ~ 2.5 at young ages. The young, cool objects hitherto thought to be substellar in mass are therefore about twice as massive, which means that the frequency of brown dwarfs and planetary mass objects in young stellar clusters has been overestimated.

Low mass objects are most self-luminous in their youth as they contract and cool. Hence, young objects offer the best opportunity for the direct detection of very-low-mass objects. There have been many efforts to identify young nearby stars to search for planetary mass companions. The K1 star AB Doradus A has long been of great interest owing to its proximity to the Sun (14.9 pc; ref. 7) and its very young age (~ 50 million years, Myr; ref. 8). AB Dor A is considered to be a pre-main-sequence (PMS) star owing to its very fast rotation period (12.3 h; ref. 9), its very strong chromospheric, ultraviolet and X-ray activities¹⁰, and its very high lithium abundance¹¹.

An age of 50 Myr is reasonable for AB Dor A because the strong lithium 6,708-Å equivalent width of AB Dor A¹¹ is similar to K stars in the 50-Myr-old cluster IC 2602 (ref. 12). Moreover, AB Dor is a member of the ‘AB Dor moving group’, which has an age of 50 Myr (refs 8, 13). AB Dor A is significantly younger than 175 Myr because it is more lithium-rich and rotates more quickly than any similar-temperature member of the 175-Myr-old M35 cluster¹⁴. Moreover, AB Dor A’s absolute visual flux is $\sim 200\%$ that of a K1 Pleiades member, as seen in the well-defined ($<10\%$ scatter) M_V versus $m_{K_s} - m_V$ colour magnitude diagram of the 125-Myr-old Pleiades cluster (see figure 4c of ref. 15). However, AB Dor A is probably more than 30 Myr old because the moving group members appear older (less H_α emission) than the 30-Myr-old Tucanae association^{8,13}. Using these independent lines of reasoning, an age of 50^{+50}_{-20} Myr is adopted for AB Dor.

AB Dor is known to have a wide companion AB Dor B^{11,16}. During the commissioning of our high-contrast camera (the new

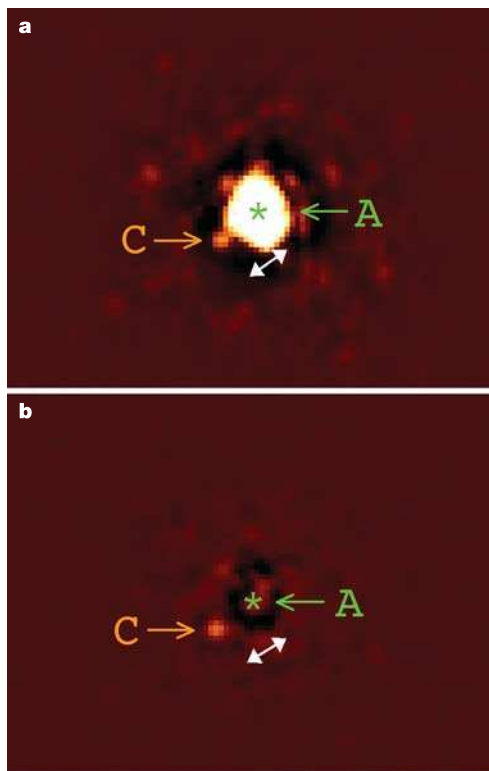


Figure 1 Discovery image of AB Dor C with the NACO SDI high contrast camera. **a**, The 1.625- μm image. **b**, The SDI of the 1.625–1.575- μm images illustrates how the SDI camera enables the subtraction of the scattered light from AB Dor A to reveal the significantly redder source AB Dor C (contrast enhanced in **b**). The white scale bar is the system separation of just 0.156". Both images have had the lowest spatial frequencies removed (unsharp-masked) to help highlight the ‘point-like’ sources in the field. AB Dor C is the faintest companion ever imaged within 0.16" of a star.

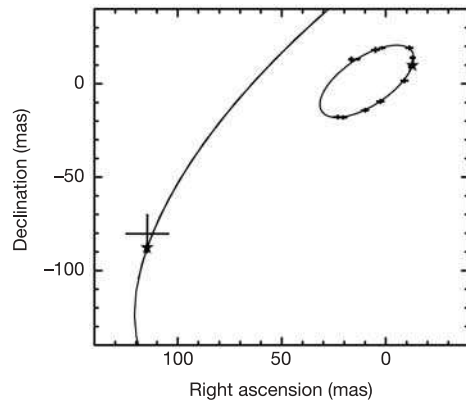


Figure 2 The AB Dor A and C orbital solution. Apparent orbits for AB Dor A’s reflex motion (inner ellipse) and AB Dor C (outer ellipse) corresponding to AB Dor A and C masses of $0.865M_\odot$ and $0.090M_\odot$ and a period of 11.75 years. Small data points on the inner ellipse correspond to the VLBI and HIPPARCOS data of ref. 17; the ‘star’ symbols correspond to the astrometric prediction of the positions of AB Dor A and C on 4 February 2004. The large cross on the outer ellipse corresponds to the latest point from the discovery of AB Dor C. AB Dor A’s reflex orbit is fitted by: period $P = 11.75 \pm 0.25$ yr; semi-major axis $a = 0.032 \pm 0.002$ "; eccentricity $e = 0.59 \pm 0.03$; periastron passage at 1991.8 ± 0.2 ; inclination $i = 67 \pm 3^\circ$; $\Omega = 132 \pm 2^\circ$; $\omega = 107 \pm 7^\circ$.

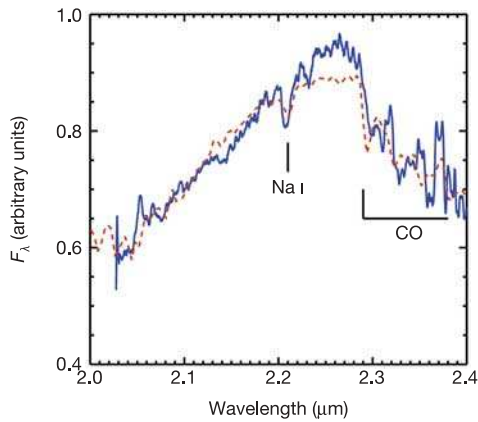


Figure 3 The spectrum of AB Dor C. The K-band spectrum of AB Dor C (solid line) as compared to the best-fit M8 template²⁹ (GL 752B; dashed line). This is the first time a spectrum has been extracted from a companion within 0.16" of a primary >80 times brighter. Note the strong 2.2- μ m Na I line due to the lower surface gravity of AB Dor C.

NACO Simultaneous Differential Imager, NACO SDI) we obtained observations of AB Dor B with the Very Large Telescope (VLT). We found it to be separated by $9.09 \pm 0.01''$ (135 AU) from AB Dor A at a position angle of $345.9 \pm 0.3^\circ$. It is a common-proper-motion companion of AB Dor A and has a spectral type of M3–M5 (refs 11, 16); it is also known as Rst 137B or HBC 434. We discovered AB Dor B itself to be a tight 0.070" binary (henceforth called AB Dor Ba, Bb) with position angle $238.6 \pm 0.3^\circ$ and a Ks flux ratio of 0.67 ± 0.06 mag.

We also detected a faint close companion to AB Dor A (Fig. 1). This companion is the very-low-mass object AB Dor C which had produced the astrometric reflex motion of AB Dor A observed by ref. 17 from very long baseline interferometry (VLBI) and HIPPARCOS data. Encouraged by this result¹⁷, the Hubble Space Telescope with NICMOS tried to detect this faint companion (R. Rebolo, personal communication) but failed owing to the

high contrast required at $<0.3''$ separations. It was not until the commissioning of our SDI camera that direct imaging of AB Dor C occurred.

Once we had identified the exact location of AB Dor C we used the normal imaging modes of NACO to detect the companion at J (1.2 μ m), H (1.65 μ m), and Ks (2.1 μ m). The companion was found to be 80 ± 15 times fainter at Ks, 120 ± 15 times fainter at H and 150 ± 30 times fainter at J (2σ errors). The location of the secondary was 0.156 ± 0.010 arcsec with a position angle of $127 \pm 1^\circ$ east of north.

To obtain an accurate measurement of the mass of AB Dor C, we used astrometric data¹⁷ to make an exploration of the orbital parameter space of the reflex motion of AB Dor A (similar to the orbit exploration described¹⁷), imposing as a constraint on the search that the predicted relative position of AB Dor A and AB Dor C was coincident, within the uncertainties, with the relative position measured on the NACO SDI detection image (to be conservative, SDI position uncertainties were increased by 50%). Because AB Dor A has $T_{\text{eff}} = 5,081$ K and $0.388L_{\odot}$, where L_{\odot} is the luminosity of the Sun, calibrated solar-mass PMS models^{1,18} predict masses of $0.853M_{\odot}$ and $0.849M_{\odot}$, where M_{\odot} is the mass of the Sun. In addition, extrapolating from empirical¹⁹ (model-independent) tracks suggests a mass of $0.893M_{\odot}$. Hence we adopt a mass of $0.865 \pm 0.034M_{\odot}$ for AB Dor A. Therefore, Kepler's third law applied to the orbital solution (see Fig. 2) yields a mass of $0.090 \pm 0.005M_{\odot}$ for AB Dor C.

At a mass of just $0.09M_{\odot}$ AB Dor C is just above the mass of a brown dwarf. Such very-low-mass ($<0.1M_{\odot}$) objects are very rare close companions ($<1\%$ of stars have brown dwarf companions at <5 AU). At a separation of just 2.3 AU, AB Dor C is the rare example of a very-low-mass object right in the middle of the 'brown dwarf desert'.

From the 2MASS 1–2.5- μ m (near-infrared) fluxes of AB Dor A (which we confirmed from our NACO observations), we derived apparent magnitudes of $m_J = 10.76^{+0.19}_{-0.24}$, $m_H = 10.04^{+0.13}_{-0.15}$ and $m_{Ks} = 9.45^{+0.12}_{-0.15}$ for AB Dor C. Using the HIPPARCOS⁷ parallax distance of 14.94 pc, AB Dor C has absolute magnitudes of $M_J = 9.89^{+0.19}_{-0.24}$, $M_H = 9.19^{+0.13}_{-0.15}$ and $M_{Ks} = 8.57^{+0.12}_{-0.15}$. The near-infrared colours of AB Dor C ($m_J - m_{Ks} = 1.3 \pm 0.4$;

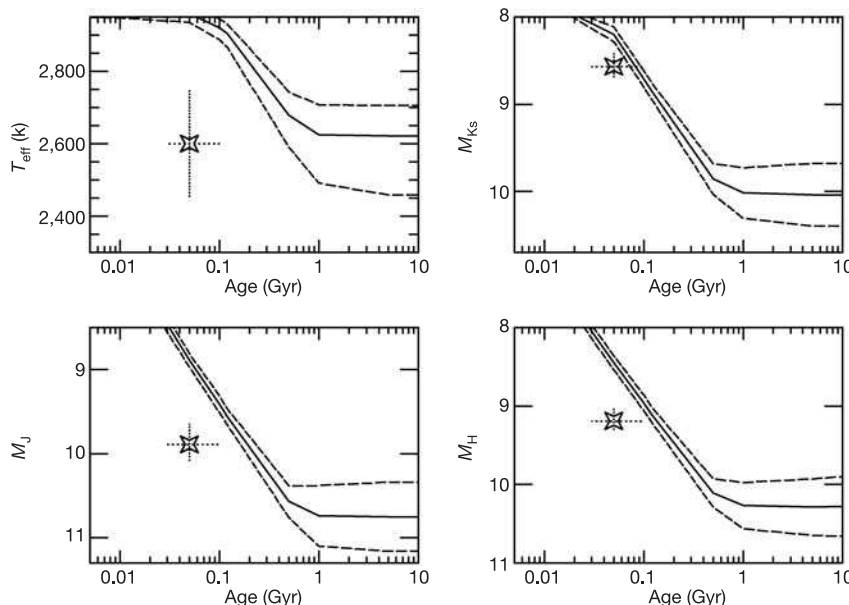


Figure 4 The observations are poorly fitted by the models. The first test of the low-mass DUSTY evolutionary tracks of ref. 1 at young ages (solid line, $0.090M_{\odot}$ track; dashed lines, $0.085M_{\odot}$ and $0.095M_{\odot}$ tracks). Note how throughout the near-infrared (J, H and Ks; 1–2.5 μ m) the models systematically overestimate the luminosity and temperature of

AB Dor C (cross shows 2σ errors). Low-mass evolutionary tracks (particularly at H and J) will have to be significantly adjusted to lower luminosities and temperatures to fit the first young mass–luminosity calibrator AB Dor C. The predicted Ks flux is closer than that of H or J.

$m_H - m_{Ks} = 0.6 \pm 0.3$) are consistent with cool M7–M9 spectral types²⁰.

To estimate better the spectral type of AB Dor C we used the NACO¹⁹ adaptive optics spectrograph. We obtained a total of 20 min of spectra with AB Dor A and C aligned along the 0.086" NACO slit. We find (see Fig. 3) that AB Dor C is best fitted by a M8 \pm 1 spectral template. This suggests an effective temperature²¹ of 2,600 \pm 150 K. From this temperature and our M_J , M_H , and M_{Ks} values we estimate²¹ a luminosity of 0.0018 \pm 0.0005 L_\odot for AB Dor C.

We note that $M_{Ks} = 8.57$ that AB Dor C is \sim 200% overluminous compared to known²² late-type (M6.5–M9) Pleiades members at 132 pc, and hence AB Dor C is probably significantly younger than \sim 125 Myr. The 200% overluminosity implies a \sim 40% larger radius than an M8 object of about the age of the Pleiades (125 Myr). Because AB Dor C would require at least \sim 60 Myr to contract to a Pleiades-sized object², it seems that AB Dor C has an age of \sim 65 Myr. This is consistent with our adopted age of 50⁺⁵⁰₋₃₀ Myr for the system.

From Fig. 4 we see that the standard 0.085 M_\odot , 0.090 M_\odot , and 0.095 M_\odot DUSTY cooling tracks¹ overestimate the near-infrared luminosity of AB Dor C. Although there is evidence²² that the DUSTY tracks fit older (\sim 5 Gyr) low-mass objects it appears that for young objects they overestimate the near-infrared fluxes. This has very significant consequences for the prediction of the mass of young low-mass stars, brown dwarfs, and extrasolar planets. In general, we predict that very young (<100 Myr), cool (1,700–2,800 K) objects will have masses significantly underestimated by the Next-Gen¹ or DUSTY¹ models. For example, the DUSTY models¹ would suggest that AB Dor C's 50-Myr age and M_J , M_H and M_{Ks} fluxes are consistent with an $M_J = 0.048 M_\odot$, $M_H = 0.052 M_\odot$ and $M_{Ks} = 0.070 M_\odot$ brown dwarf, respectively. The predicted mass from the M_{Ks} flux of 0.070 M_\odot is most accurate, yet is still a significant underestimation. The other popular set of brown-dwarf models² predict a mass of 0.038 M_\odot for a 50-Myr-old object with $T_{\text{eff}} = 2,600$ K. In general, substellar models^{1,2} predict masses for AB Dor C that underestimate the true 0.090 \pm 0.005 M_\odot dynamical mass by a factor of two. Such errors will require serious revision of the frequency for the lowest-mass objects (brown dwarfs and extrasolar planets) at young ages.

One direct consequence is that the masses quoted from the DUSTY models for the young objects in deep H and J surveys of the Trapezium Orion²⁴ and σ Orionis²⁵ clusters are not significantly less than the deuterium-burning mass limit (\sim 0.013 M_\odot) when we lower the luminosity of all the tracks by a constant offset of one magnitude (as required to fit the H and J tracks to the observations of AB Dor C). This has the very significant effect of increasing the mass of the lowest luminosity ($M_H \approx 9.7$ at 1 Myr; ref. 24) members of the Initial Mass Function (IMF) above 0.013 M_\odot . Moreover, the current class of free-floating 'cluster-planets' of $T_{\text{eff}} \approx 1,700$ –2,800 K may be misidentified low-mass brown dwarfs (the one 'free-floating planet' too cool (<1,200 K) to apply the DUSTY models for a mass derivation is probably a more-massive-field brown dwarf²⁶). In general, this paper illustrates the danger of using evolutionary tracks at ages that have not been fully calibrated by observations. \square

Methods

Simultaneous differential imaging with the new NACO SDI camera

Because of AB Dor's youth and proximity we observed it during commissioning of a new high-contrast adaptive optics camera (NACO SDI^{4,6}). This camera creates four nearly identical simultaneous images of the star and passes this light through three different narrowband methane filters (1.575, 1.600 and 1.625 μm). Because methane has a strong absorption redwards of 1.61 μm , the subtractions of the star's image from 1.575–1.625 μm will remove the star's scattered light halo and reveal any methane-rich planets that were hidden in the glare of the star. This technique of SDI was developed elsewhere²⁷ and has achieved only mixed success before NACO SDI.

To fully capitalize on the power of the SDI technique we^{4,5} developed a double Wollaston beamsplitter which creates four nearly identical images with only 10 nm root-mean-square (r.m.s.) of wavefront error between them. In addition, we developed a very-high-quality glass flat coated with three narrowband 'panel' filters deposited over the four quadrants⁴. When combined with new $\lambda/30$ quality $f/40$ relay optics⁵ (where λ is wavelength and $f/40$ is the focal ratio), we had an optimal SDI camera. This camera is now fully integrated into the facility adaptive optics camera CONICA²⁷ which is fed by the NACO adaptive optics system at the 8-m VLT of the European Southern Observatory (ESO). Our new SDI optics enable a new high-contrast mode for the VLT's NACO²⁸ adaptive optics system. We have found that on bright targets it is possible to reach the theoretical photon-noise limit ($\Delta H = 11$; contrasts of \sim 25,000) in 40 min at 0.5" at 6 σ when using SDI to look for faint methane-rich ($T_{\text{eff}} < 1,200$ K) companions⁶.

During our observations (2 February 2004 UT) of AB Dor we noticed a point-source structure very near the 0.06" full-width at half-maximum (FWHM) core of AB Dor (Fig. 1a). Because the SDI camera does not require a coronagraph we can image within 0.1" ($2\lambda/D$) of the star, where D is the telescope's diameter. This source was just 0.15" from the centre of the star and was not fully subtracted out in the SDI difference images (scattered light, or 'speckles', from the star would normally be strongly attenuated by the SDI pipeline⁶). In particular, the 1.625–1.575- μm difference image from our data reduction pipeline⁶ showed what appeared to be a faint companion (Fig. 1b). The intensity was positive in the 1.625–1.575- μm image, so the point source was not methane-rich (and hence was hotter than 1,200 K) but not as hot as the AB Dor A (spectral type K1V; $T_{\text{eff}} \approx 5,080$ K; ref. 11). We confirmed that the object was a real companion by 'rolling' the VLT's derotator from 0° to 33° and obtaining another SDI data set. As expected for a real companion, the point source indeed rotated with the sky by 33°.

Near-infrared broadband imaging with adaptive optics

Once we had identified the exact location of AB Dor C we used the normal 0.013"/pixel imaging modes of NACO to detect the companion at J (1.2 μm), H (1.65 μm), and Ks (2.1 μm). We used an observation pattern similar to that used with the SDI camera. To better enable detectivity we obtained images at derotator rolls of 0° and 180°. The data reduction used the adaptive-optics data reduction pipeline of ref. 20. In addition, we replaced the saturated core of AB Dor A with scaled unsaturated (0.36 s exposure) data from the AB Dor's acquisition image. To enhance the signal from AB Dor C we subtracted the 180° images from the 0° images. Scaled images of the AB Dor A point spread function (PSF) were custom-shifted and subtracted from the 0–180° image at the location of C until the companion's signature was removed.

Near-infrared spectra with adaptive optics

To measure the spectral type of AB Dor C we used a $R \approx 1,200$ –1,500 (2–2.5 μm) grism with the 0.027" per pixel camera of NACO²⁸. We obtained a total of 20 min of spectra with AB Dor A and C aligned along the 0.086" NACO slit. Eight relatively deep exposures were taken, saturating the core of the AB Dor A spectra, but leaving the wings, containing the signal from AB Dor C, intact. The two objects were nodded along the slit between exposures, and the derotator was rotated by 180°, and the sequence of exposures was repeated. In addition, we obtained four unsaturated spectra of AB Dor A. Strips of unsaturated pixels containing the spectra of AB Dor C were then extracted, wavelength-calibrated, and combined using standard Image Reduction and Analysis Facility (IRAF) routines. Removal of the telluric lines was done via spectra of a G3 standard star (HIP 24153) taken within 30 min of our science exposures, and features from the calibration star were removed using a modified solar spectrum³⁰. Finally, the high signal-to-noise unsaturated AB Dor A observations are subtracted from the extracted spectrum to reveal the spectrum of the companion (see Fig. 3).

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High-velocity streams of dust originating from Saturn

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High-velocity submicrometre-sized dust particles expelled from the jovian system have been identified by dust detectors on board several spacecraft^{1,2}. On the basis of periodicities in the dust impact rate, Jupiter's moon Io was found to be the dominant source of the streams³. The grains become positively charged

within the plasma environment of Jupiter's magnetosphere, and gain energy from its co-rotational electric field⁴. Outside the magnetosphere, the dynamics of the grains are governed by the interaction with the interplanetary magnetic field that eventually forms the streams⁵. A similar process was suggested for Saturn⁶. Here we report the discovery by the Cassini spacecraft of bursts of high-velocity dust particles ($\geq 100 \text{ km s}^{-1}$) within ~ 70 million kilometres of Saturn. Most of the particles detected at large distances appear to originate from the outskirts of Saturn's outermost main ring. All bursts of dust impacts detected within 150 Saturn radii are characterized by impact directions markedly different from those measured between the bursts, and they clearly coincide with the spacecraft's traversals through streams of compressed solar wind.

In agreement with model predictions for the interplanetary dust environment between Jupiter and Saturn, the cosmic dust analyser⁷ (CDA) on Cassini registered almost no dust impacts during the late phase of the spacecraft's cruise to Saturn. But beginning in 2004 when Cassini was closer to Saturn than $1,200R_S$ (Saturn's radius $R_S = 60,330 \text{ km}$), two faint impact bursts by high-velocity grains were observed. Remarkably, the burst intensity seemed to grow as Cassini approached Saturn (see Fig. 1), which indicates a saturnian origin of the impactors. Interplanetary dust can be excluded as the source by examining the transmitted impact signals. At 8.5 AU from the Sun, interplanetary particles moving in bound orbits about the Sun hit the Cassini dust detector with velocities below $10 \text{ km s}^{-1} (1 + \max(e))^{1/2} + \max(v_{sc}) \approx 20 \text{ km s}^{-1}$, where $e < 1$ is the eccentricity and $v_{sc} < 6 \text{ km s}^{-1}$ is the inertial spacecraft velocity. (Here one astronomical unit, AU, is the average Earth–Sun distance.) According to the CDA calibration, impact speeds of about 20 km s^{-1} will lead to rise times of the ion grid signal longer than $18 \mu\text{s}$, which is much longer than the observed rise times of below $3 \mu\text{s}$. In fact, the transmitted signals are steeper than the fastest calibration impact of about 70 km s^{-1} recorded at the Heidelberg dust accelerator facility (Fig. 2). Consequently, the impact speed of the grains comprising the bursts even exceeds 70 km s^{-1} , which excludes bound interplanetary grains as the source. Further, before Cassini's Saturn orbit insertion the CDA detector was geometrically insensitive to fast interplanetary dust in unbound orbits (the so-called β -meteoroids⁸) as well as to interstellar particles. These observations justify our considering the saturnian system as the origin of the observed particles.

There is, however, a striking similarity in both the rise time and the amplitude of the impact signals produced by saturnian dust grains and those produced by jovian stream particles recorded by CDA during Cassini's fly-by of Jupiter in 2000 (Fig. 2), suggesting that the mass and the impact speeds are at least comparable. This implies, however, that the mass and the impact speed of the detected particles are well outside the calibrated range, and that the standard techniques to derive the dust mass and the collision velocity from the impact signals⁹ cannot be applied to them. We benefit from the fact that the characteristic properties of jovian stream particles are known from theoretical considerations. It was shown¹⁰ that such particles had velocities exceeding 200 km s^{-1} and charge-to-mass ratios of $1,000 \text{ C kg}^{-1}$ (corresponding to grain sizes below 10 nm). We therefore conclude that the impact signals registered by Cassini were due to grains with impact speeds in excess of 100 km s^{-1} and with a typical mass below 10^{-21} kg .

The potential mechanism accelerating particles within Jupiter's and Saturn's magnetosphere to such a high velocity has been discussed in great detail in the literature^{5,6,11}, so we simply summarize the basic concept. Positively charged grains will be accelerated outward by the outward-pointing co-rotational electric field caused by Saturn's rotating magnetic field. Possible sources of positively charged dust in Saturn's magnetosphere are the dense A ring outside the synchronous radius at $1.86R_S$, the E ring, and the