Planet Earth Building-Blocks – a Legacy eMERLIN Survey (PEBBLES)

Executive Summary

We propose an ultra-deep continuum survey of the circumstellar disks that are predicted to be the most conducive to planet formation. Imaging the thermal emission from pebble-sized dust grains will show where and when planet-core growth is proceeding, and identify actual accreting proto-planets. The survey sample comprises a mass-limited cut from all known northern disks with long-millimetre wavelength dust emission, above a threshold of 2.5 times the minimum-mass Solar-nebula, at the theoretical boundary for forming the Sun's planets. The sample is otherwise unbiased and includes 19 young stellar objects with imageable disks in 13 fields, at distances <250 pc so that at 40 mas resolution the terrestrial planet zone is separated from that of gas giant formation. The span of stellar ages is ~0.1-7 Myr, i.e. the epochs of gas giant growth and early assembly stages of terrestrial planets. All systems will be imaged at C-band (5 cm) to a uniform mass depth of a few $M_{\rm Earth}$ of dust (in the beam containing the Earth-formation zone), requiring 468 hours in total including the Lovell Telescope. This will be the first survey of the inner disk regions at a few AU resolution and will exploit the uniquely optically-thin flux from these zones of very high column density. The survey results will show how planet growth proceeds – where, when, and with what outcomes – for comparison to the inferred histories of the Sun and extrasolar planetary systems, and to our simulation results based on current planet-formation models. The scientific legacy will also include measuring quantities vital to theoretical progress – particle sizes, disk surface densities and radial distributions, for the first time on few-AU scales – and providing a database of proto-planet targets for future followup with EVLA, ALMA and SKA.

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Introduction

Overview

Since the discovery of the first extrasolar planets around main-sequence stars in 1995, the field of planet-formation studies has been very active. Understanding the origins of planetary systems allows us to put our Solar System in context: is this particular arrangement of bodies likely to be common or unusual? and does this relate to the development of life on Earth? The details for sustaining life are complex (liquid water, volatile atmosphere, plate tectonics etc., Raymond et al. 2007) and may be a rather subtle outcome of the planet formation process, in terms of the Earth's final location and mass. Unfortunately, this regime of parameter space is exactly the one that is hardest to observe directly. Planet detection techniques now approach close to the 1 Earth -mass regime, but only in the special circumstances of hot rocky bodies detectable by Doppler wobble or transit (mainly around red dwarfs) or microlensing by icy planets orbiting at a few AU around distant stars (with limited follow-up opportunity). Imaging of Earth-mass planets around Sun-like stars by space interferometers is still a technically distant prospect – but eMERLIN offers a chance now to observe the *formation* of inner-system terrestrial and giant planets, via the blackbody emission of very large dust grains (few-cm-sized, i.e 'pebbles').

Observational studies of young circumstellar disks have so far been made mainly in the infrared to millimetre, where moderately optically-thick continuum and line emission can probe the distribution of dust and gas. Some of the results are puzzling, such as a very wide range of disk masses and sizes for T Tauri stars (Andrews & Williams 2007a,b). Often the internal mass distributions appear unconducive to planet formation, when seen at tens of AU resolution, with shallow profiles extending to several times the Solar System radius. The derived surface densities of solids then appear to be below the threshold needed to initiate core growth (Hubickyj et al. 2005). These anomalies raise the question of whether even the right disks are being observed: if planets formed rapidly along with the star itself, in the protostellar phase, the most commonly-studied classical T Tauri stars could actually represent *post*-planetary disks. The timescales for growth are very uncertain due to a critical breakdown in the process: collisions among mm-sized dust aggregates can be destructive rather than progressing to cm-sized bodies (Wurm et al. 2005).

The eMERLIN opportunity is very timely, as we can now observe exactly this size regime of dust, to see in what circumstances actual disks overcome this problem to proceed to make planets. High-resolution radio interferometry is ideally matched to the scales of inner proto-planetary systems in nearby star-formation regions, and also to the thermal signature of very large grains. Particles emit wavelengths larger than their size very inefficiently and so 'pebbles' are a pre-requisite for radio emission from dust. This will be the first time it is possible to observe the disks *at resolutions of a few AU* (so that inner terrestrial planets can be separated from the orbits of gas giants) with sensitivity to a few Earth-masses of planet-forming material. By surveying candidate proto-planetary disks, we can discover which systems have rocky material growing into planetesimals, determine where within the disk this growth occurs in relation to planet orbits, and even directly image rocky material in condensing proto-planets (as for the HL Tau b archetype, Figure 1). The results can be used immediately to inform planet-formation theory and to compare to extrasolar planetary systems as these discoveries gradually approach the Solar System regime.

Models of Planet Formation

Today there is consensus about the general process by which circumstellar gas and dust form into planets (see e.g. Ida & Lin 2004, Chambers 2004) but some of the details present theoretical problems. The standard scenario is that planets form within circumstellar disks that also provide a conduit for the transport of angular momentum outwards, allowing mass to accrete onto the central star. The disk inherits an initial gas-to-dust mass ratio of ~100 from the interstellar medium, but collisions allow the dust to grow rapidly in the dense disk. Gas drag then causes the solid particles to sediment down towards the mid-plane, while the bulk of the mass in gas remains in pressure supported layers with a larger vertical scale height. The solids in the midplane may then grow rapidly to form the planesimals that coagulate to become the cores of gas giant planets, or later merge to form terrestrial planets. The key to the formation of planets, in particular gas giants, is in forming these large stable bodies quickly enough so that they can (if sufficiently massive) gravitationally attract gas envelopes before photo-evaporation removes the disk volatiles. The planet formation process is accelerated beyond the 'snowline'at ~3 AU where ice mantles form on dust grains, so enhancing the amount of planet-forming material, and making this material more likely to stick together in collisions. Inward radial migration can occur through interaction with the surrounding gas disk, ultimately producing gas giant planets over a range of orbital radii within a few Myr, although problems exist for excessive migration (into the star) and radiating enough heat to allow planets to contract. Alternative models can speed up the process in massive disks, where compact gravitationally-unstable regions can fragment out directly to form a proto-planetary condensation in a few orbital periods, although the uncertain equations of state mean that it is unclear how well this can operate in the inner disk. In either case, remnant planetesimals will persist for timescales of a few to tens of Myr, and encounters will allow merging in a runaway growth process. As planetary embryos reach Mars-like sizes, perturbations slow the rate of mergers, but gravitational focussing allows the largest bodies to sweep up surrounding material in an oligarchic growth process. This results in a small number of inner-system terrestrial planets completed by ~10+ Myr, with thin atmospheres and potentially surface water, collected from the now gas-poor disk and/or delivered by late impacts of remaining planetesimals.

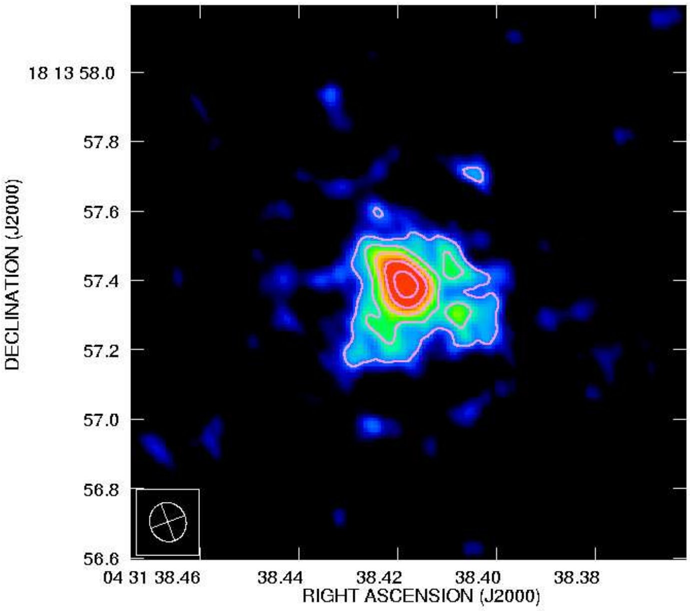

Figure 1: HL Tau disk at 1.3 cm with a resolution equivalent to Jupiter's orbit (size of central unresolved peak). NE/SW features are bases of the jets and NW, SE lobes are the ends of an inclined disk extending to ~Neptune's orbit. The marginally resolved candidate proto-planet at 55 AU is to the NW (upper right).

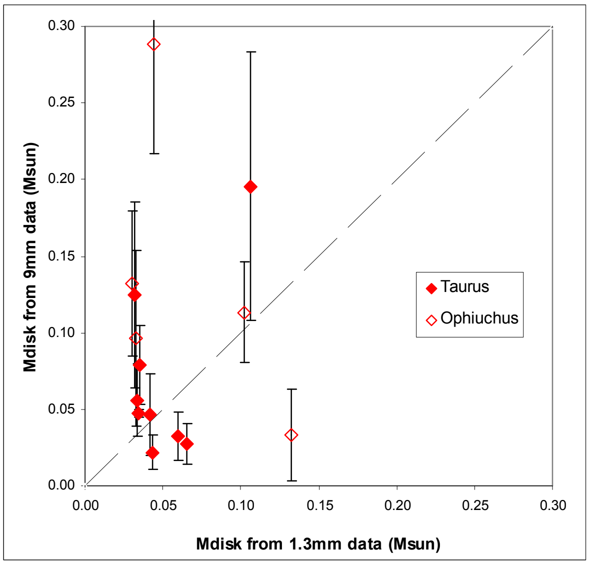

Figure 2: Disk masses for Class II objects in Taurus and Ophiuchus, from 9 and 1.3 mm dust fluxes (Greaves et al., in prep.). The cm-based masses are typically higher (factors up to 5) than the mm-based values, and the disks with lower mm-based masses are more often increased.

Observational Results for Planets and Disks

There is evidence from the Solar System and exo-planet systems that these theories are broadly correct. Saturn, Uranus and Neptune have ~15 M_{Earth} solid cores (Saumon & Guillot 2004; uncertainties in equations of state formally allow Jupiter to have a negligible core). The Solar System's initial mass budget thus needed to be ~50 M_{Earth} in solids and so 20 $M_{Jupiter}$ (0.02 M_{Sun}) in gas for an initial mass-ratio of 100 (Davis 2005). The Minimum Mass Solar Nebula (MMSN: Hayashi 1981, Weidenschilling 2000) must therefore have been substantial, and core accretion models suggest that ~2.5-MMSN (0.05 M_{Sun}) is needed for Jupiter to form within a few Myr (Rice

& Armitage 2003). Transit results on mass-radius relations show that some extrasolar gas giants have cores of as much as 70 M_{Earth} (Sato et al. 2005), and so even more substantial primordial disks may be required. Long-mm wavelength data that are sensitive to the mass reservoir in large grains are pointing to increased estimates for masses for disks (Rodmann et al. 2006), making the overall disk population more favourable for planet growth by core accretion and/or gravitational instability (when planet-cores may perhaps form later by dust settling, Helled et al. 2008). Greaves et al. (2008) found that the Class I protostar HL Tau has an unstable disk of ~1/2 the stellar mass, and observed a compact radio feature that is a candidate proto-planet of ~10-14 $M_{Jupiter}$ (Figure 1).

Evidence for model timescales being roughly correct comes from D/H-diffusion dating of the giant planets, with Jupiter and Saturn being >0.7, >5.7 Myr older than the Sun (Hersant et al. 2001). This is consistent with the oldest ages when gas needed to supply giant-planet atmospheres is still seen in disks (~15 Myr, Dent et al. 2005). When the Earth formed is uncertain, because of contamination and differentiation effects on the radio-isotopes used for dating. Earth and Mars are likely to have been completed about 40-60 Myr after the Sun formed (Touboul et al. 2007, Caro et al. 2008), but dating of asteroids suggests that planetesimals were available to start forming terrestrial planets within the first few Myr. Inwards migration of hot Jupiters may scatter such planetesimals but over half are predicted to survive, with a 1 M_{Earth} body at 1 AU amalgamating as early as 10 Myr (Fogg & Nelson 2007, Raymond et al. 2008). Terrestrial planets could be common, with ~1/2 of young dust disks having a solid reservoir of ≥5 M_{Earth} (Greaves et al. 2007).

A significant problem exists in explaining the ~15% frequency of gas giants around Sun-like stars in long-term Doppler surveys (Fischer et al. 2003). Millimetre data for Class II Tau/Oph stars (Andrews & Williams 2007b) shows that the mean disk mass is only ~5 $M_{Jupiter}$ (one-quarter of an MMSN), while analysis for seven star-clusters (Greaves, Rice & Wood in prep.) finds that only ~5% of stars seem to host 1 MMSN of dust. These results contradict the observed ~15% incidence of gas giants and the >1-MMSN required to make massive exo-planet systems. This suggests either that bulk disk masses are underestimated – perhaps because solid mass locked up in large grains has not been accounted for (Figure 2) – or that grain growth may occur earlier than suspected, e.g. around <1 Myr-old Class 0/I protostars – these are short-lived and thus rarer, and only a handful have been studied in detail. A survey investigating both these possibilities, to see when and how dust grows towards planets, is thus very timely and is the basis of our proposal.

Rationale for Radio Observations

Super-grains a few centimetres in size are needed to produce thermal radio emission. A mm-to-cm spectral index approaching a blackbody ($F_\nu \propto \nu^{2\rightarrow3}$) is indicative of particles ≥3× the observing wavelength (Draine 2006), and is highly distinctive versus nearly-flat spectra of ionized stellar winds ($\nu^{-0.1\rightarrow1}$), or the steep spectrum ($\nu^{3.5\rightarrow4}$) of a grain population truncating at small sizes. Super-grains are associated with the dense disk mid-plane where there is rapid growth, and not with more diffuse regions (e.g. Fig. 5 in D'Alessio et al. 1997, showing three orders of magnitude less cm-flux from the HL Tau protostellar envelope than the disk). Observations at a few cm can thus pinpoint the locations of pebbles *10 cm or more in size* – well down the path to planet formation, in the progression from sub-micron interstellar grains originally populating the disk (5 orders of magnitude growth) to 1000-km-class planetary bodies (a further 7 orders of magnitude).

Radio-regime dust observations have been severely limited by sensitivity with e.g. only a handful of 1.3 cm studies made so far (Greaves et al. 2008, Choi et al. 2007, Rodmann et al. 2006) – pebbles are simply very weak emitters, locking up substantial mass within relatively little emitting surface. What happens to the mass as it evolves through this size scale is hard to track, so we are missing a stage between small dust seen in bright IR/mm radiation and large planetary bodies detected via the gravitational effects on the star. Yet cm-sizes are a key regime, as high-speed particle collisions need to lead predominantly to coagulation of mm-sized bodies rather than destructive fragmentation. Our experimental studies (Wurm, Fraser) are beginning to suggest how such grains can aggregate, e.g. by greater stickiness of ices, and these results can constrain properties of particles that would exist in disks, and hence real emissivities needed to measure the disk masses in the planet-forming context. In PEBBLES, we are proposing to put experiment and theory together with ground-breaking high-resolution (40 mas) observations, to discover in what circumstances real disks proceed to decimetre grain sizes and onwards towards planets.

A particular benefit of radio imaging is that the flux distribution can be readily interpreted and modelled in simulations. The radio emission of dust is optically thin and so gives a temperature-weighted mass for each line of sight in the image. Dust temperatures can be found from thermal equilibrium with the star and checked in our radiative transfer models (Wood 2008), and the mass is only otherwise dependent on the stellar distance and the grain emissivity. The latter has recently been calculated for grain populations extending up to metre-sizes (Draine 2006) and for pebbles the emissivity is relatively insensitive to composition and structure issues that affect shorter wavelengths. We thus expect to measure dust-disk masses accurate to within a factor of 2, i.e. of very good quality for comparing with requirements for planet cores to form in simulations. Observations with eMERLIN at 5 cm wavelength can detect a few Earth-masses of dust per beam (see Technical Case), for the first time in the regime needed to study the formation of planetary cores. The gas mass reservoirs in the disks will not be measured in this project, but most of our targets are expected to be observed in Herschel Key Projects (GASPS and DIGIT) – this low-resolution data on the least chemically-variable tracers such as [OI] will produce the best estimates so far of the bulk masses in gas. This aspect is important for comparison of the disks to the masses of observed exoplanet systems, but is much less critical for understanding planet formation compared to following the initial stage of the growth of rocky cores.

Science Questions and Outcomes

PEBBLES aims to address some of the most fundamental questions in planet formation – *do we understand the growth mechanisms correctly? do planets form in similar orbits around all stars? are terrestrial and giant planets formed around stars of all masses? do all massive disks succeed in forming large bodies out of primordial dust? what is the critical phase when rocky bodies are built? do disks need certain structures such as a central peak for planet formation to succeed?* These most basic issues are very unclear at the moment, with theories not well constrained by observations and too many inferences based on the details of the Solar System.

The following observation-focussed questions summarise the science drivers for the survey:

(1) which circumstellar disks proceed to the stage of forming decimetre-sized solid bodies?

(2) where does this growth occur within the disks?

(3) what mass reservoir is involved, and is planet formation seen to be actually taking place?

Our approach will be to target the stars that appear to have the *highest planet-forming potential*, specified as hosting disks with the highest dust masses and at least millimetre-sized grains. We will image the inner few AU of all these (northern) disks of ≥2.5 MMSN, i.e. the approximate mass in core-accretion models needed for planets to grow efficiently (solid surface density of ~5 cm^2/g at 5 AU assuming a Solar System-like radius of 50 AU). Each image will be at comparable spatial resolution (i.e. a restricted range of stellar distances), and adequate to resolve the terrestrial planet zone from the region outside the snowline (~3 AU) where giant planets form. Sensitivity to dust mass will be uniform and deep enough to detect a few Earth-masses of dust per beam.

The science driver questions can then be addressed using quantities that are robustly measureable from the images, allowing direct tests of which hypotheses are possible and which are ruled out – For **(1)**, largest grain sizes can be calculated from the spectral index: for flux $F_\nu \propto \nu^{2+\beta}$ the latter term represents the dust opacity index $\kappa \propto \nu^\beta$ which is lower for larger particles (Draine 2006). The majority of the mass is in these largest particles and so their flux and emissivity yields the solid mass up to decimetre sizes. This mass will be related to properties of the target stars (see

Table A1 in the Appendix) to test whether grain growth advances at particular evolutionary stages or ages, or around stars of particular mass or situations of dynamical instability (e.g. binaries).
For **(2)**, the dust flux density and opacity index can be plotted as a function of radius in the disk, to compare the zones with the highest mass in large grains to the predictions of models for how fast grains will grow for the local dynamical time, and experimental collisional sticking probabilities. This will show if giant and terrestrial planets can form in the expected places, times and sequence.
For **(3)**, the minimum solids-reservoir in large grains can be compared to the requirements in accretion models for planet cores to grow efficiently, and dust masses can be converted to esimated gas-disk masses to see if disk-to-star mass ratios are high enough for gravitational instability to operate. The masses and sizes of imaged condensations will be compared to model predictions for accreting proto-planets (the Hill radius can just be resolved for massive bodies, Figure 1), and the nature of these as future terrestrial or gas-giant planets can be assessed.

Survey Strategy

The approach of observing the most massive disks is dictated by the extreme faintness of pebble emission, and the consequent need for a high data return rate from a small number of fields (possible biases are discussed below). We are therefore proposing a survey of the *most promising* disks for planet-formation, not an unbiased survey – our rationale is a strong test of prevailing theories, as e.g. if dust growth is *not* occurring, then the basic ideas must be radically re-addressed.

We need targets with evidence of ongoing grain growth, and select these by dust detection at long millimetre wavelengths, with confirmation by (sub)arcsec interferometry that the flux originates from a compact disk. The targets have 3-13 mm dust detections (most commonly 7 mm VLA data) and are from a complete literature survey plus some of our own unpublished results. The long-mm flux is dominated by dust but corrections for free-free emission have been made in all cases, using 2-6 cm measurements from the literature and archival data.

These residual dust fluxes representing moderately large grains were then extrapolated to the chosen eMERLIN wavelength of 5 cm, assuming $F_\nu \propto \nu^{2+\beta}$ and two alternative cases of $\beta = 0, 0.3$. The former represents efficient growth to large blackbody particles, while the latter is the mean observed long-mm spectral index in the sample. In fact the targets are very promising for demonstrating grain growth at a range of efficiencies, with a β-range of –0.1 to 0.8. The existence of grains of decimetre sizes is confirmed from the only long-cm data obtained so far (the southern star TW Hya, Wilner et al. 2005) where $\beta = 0.1$ out to 3.5 cm wavelength. As we are interested in maximum growth, we adopt β=0 for flux predictions, noting that the fluxes are halved for β=0.3.

Our basic MMSN model assumes 0.02 M_{Sun} in a centrally concentrated disk (75% of the material inside Saturn's orbit; Davis 2005) with the dust mass dominated by large grains and a gas-to-dust mass ratio of 100. A pre-main sequence Sun-precursor (e.g. 2 L_{Sun} at 1 Myr, K5 spectral type) will have $T_{dust} = 330\text{K} / r_{AU}^{0.5}$ in thermal equlibrium (Backman & Paresce 1993), and the dust emissivity adopted is $\kappa_{1.3cm} = 7\times10^{-5}$ m^2/kg (Draine 2006). The flux contributions are calculated for annuli the width of the C-band beam, e.g. for the Taurus association distance at 140 pc, 40 mas = 5.6 AU. The total MMSN flux at 5 cm is then ~15 μJy for $r^{-1\rightarrow-1.5}$ surface density profiles and blackbody grains (for details, see Technical Case), and imaging above ~3σ per beam (rms = 1.3 μJy/beam) is possible out to at least Jupiter's orbit. We adopt 15 μJy as the basic 'MMSN unit' (adjusted for distance), and identified 19 disks above 2.5 MMSN out of 45 northern objects within 250 pc having long-mm data (Figure 3). Our detailed disk-image simulation is shown in Figure 4.

Our *mass-cut target list* comprises these 19 massive disks, at distances of ~130-220 pc (i.e. spatial resolution uniform to ±25%). To avoid biases, no further cuts were made on any hypothetical grounds, such as degree of disk central concentration, presence of perturbing stellar companions etc.. The sample in fact covers a wide range of properties (Table A1), including the full range of evolutionary stages (Classes 0, I, II) where disks are suspected to be planet-forming, and estimated stellar ages from ~0.1-7 Myr. Ages of individual stars are subject to uncertainties in evolutionary tracks (e.g. Hillenbrand 1997) but the spread of classes implies that diverse mass reservoirs are present and so all stages of planet formation should be ongoing. The A-to-M spectral types are well matched onto exo-planet hosts (e.g. Doppler targets including F-to-M dwarfs and sub-giants descended from A-stars). A range of star-forming environments is included, comprising 10 disks in the L1551 and NGC 1333 clusters, 7 disks in the Taurus filaments and 2 more isolated stars.

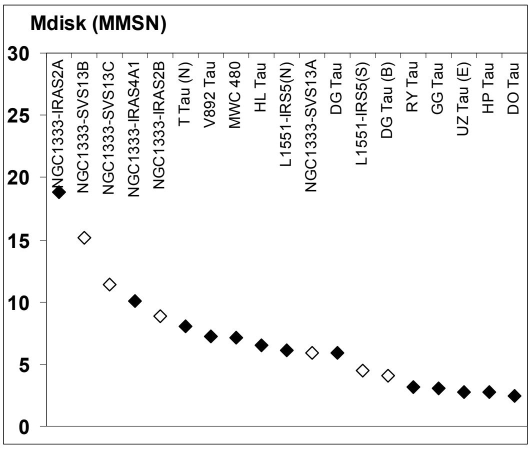

Figure 3: Mass-ordered plot of the 19 target disks in PEBBLES, from 2.5-19 MMSN. Unfilled symbols are disks lying in the same eMERLIN field as a brighter object.

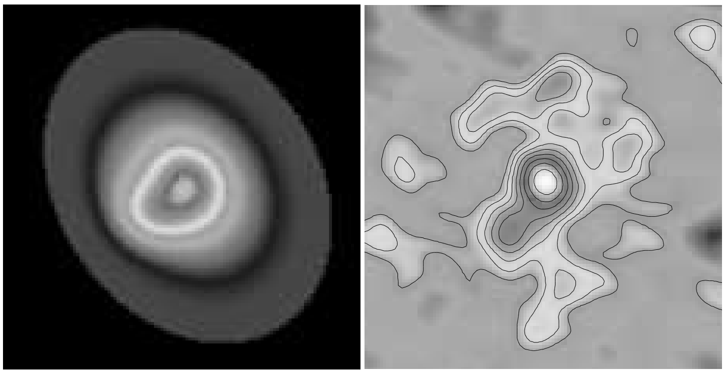

Figure 4: Model $r^{-1.5}$-profile disk and predicted eMERLIN image at 5 cm, from simulation at PEBBLES bandwidth and depth plus reduction with correct baseline weighting (60 mas restoring beam). Total flux is 150 µJy (~10 MMSN at 140 pc). The simulation clearly shows the inner disk to 7 AU (50 mas) and a proto-planet at 13 AU. Images: 500 mas across.

Statistics and Biases

The mass-limited survey must be carefully interpreted, to avoid propogating misconceptions in the later literature e.g. that most disks are planet-forming. Generally statistics are not the aim of the survey, which addresses *how* rather than *whether* planet formation proceeds. The scientific breakthrough of our survey comes from obtaining 19 very detailed images of planet formation in action, for comparison and testing of different models – this is a huge leap over the single system imaged so far at comparable resolution (Figure 1). However, within this moderate sample, any properties that very strongly influence planet-forming outcomes could in fact be distinguished. Many of the properties allow a division into two roughly equal subsets, e.g. (Table 1) there are 10 very young stars (≤0.3 Myr) compared to 9 older objects, and 7 high-mass stars versus 12 of ~1 M_{Sun} or less. If an outcome such as efficient grain growth is strongly linked to such a property, this could be demonstrated with robust statistics depending on the actual object counts. For example, for a property seen within two half-samples at rates of only one disk (≤ 22% from (1 ± 1) / 9 with Poisson statistics) versus all the disks (>= 67% from (9 ± 3) / 9), these incidences would differ with >99.9% confidence in a student's-t test. Thus, if any star or disk property is *essential* to successful planet formation, we can show this rigorously within the relatively small sample.

The main difficulty of our approach is in drawing conclusions about planet formation for the *general* ensemble of young stars. For example, low-mass disks that we can not observe in PEBBLES might form terrestrial planets very successfully but not have the capability to form gas giants, so we could miss some modes of planet formation. We therefore considered other possible strategies – but found that none of these yield as much scientific outcome.

- An *unbiased* survey of 19 disks chosen at random would be unproductive. Only up to 4 would lie above the 2.5-MMSN level that we can image (using the 1mm disk-mass distribution of Andrews & Williams (2007b) and the highest boost to mm-based disk masses in Figure 2). Any deductions about planet-formation would thus be very skewed by individual systems. If many disks could be studied, an unbiased survey would be ideal, in case we miss objects simply because no long-mm data have been taken. However, checks of 1mm Taurus data uncover only ~3 disks that are in the MMSN-regime but have no longer-wavelength results, so missing systems should be negligible.

- A *control group* of stars could be used to check if disks with high planet-forming potential have been missed, e.g. cm-bright but for some reason not prominent in the long-mm. In fact, there are 22 more young stars within the central 3 arcmin fields-of-view, i.e. other region members and secondaries, which have disks of lower or negligible mass but that could be detected if cm-enhanced in dust. These boost the possible detections to 41 objects in 13 fields, and supply an automatic control group without adding any time-consuming extra observations.
- A *single star-forming region* could be observed, to impose uniform spatial resolution and initial conditions. However, Taurus is the only well-populated northern region where different planet-forming zones can be resolved, and it is atypical as a sparse rather than clustered mode of star formation, and less representative of Solar origins. (A supernova near the young Sun is thought to have injected rare isotopes, and a massive progenitor is more likely in a cluster.) Varied environments should also be a better match to the range of birth-sites of extrasolar planets.
- A strategy for observing *terrestrial planet formation* could include older stars, up to ~50 Myr. However the PEBBLES targets include stars a few Myr old where rocky planets should already be forming (Raymond et al. 2007). In case grain growth could be slower than predicted, we made test observations of an ~30 Myr old star with far-IR excess (HD 377, Hillenbrand et al. 2008), using rapid-response time at GBT in August 2008. No 1-cm dust emission exists above 0.3 mJy, or <0.1 MMSN at 40 pc, suggesting such older dusty stars may be in a post-planet-forming debris phase.

In summary, none of these alternative strategies would be as productive as our adopted mass-limited cut of all known disks with evidence of grain growth. In all resulting publications we will make it clear that this is a survey of disks with the highest planet-forming potential, rather than of all possible disk types. PEBBLES will investigate a subset of planet-building modes, similarly to exo-planet Doppler surveys that are more sensitive to higher-mass and smaller-orbit planets.

Analysis Methods

Interpretation

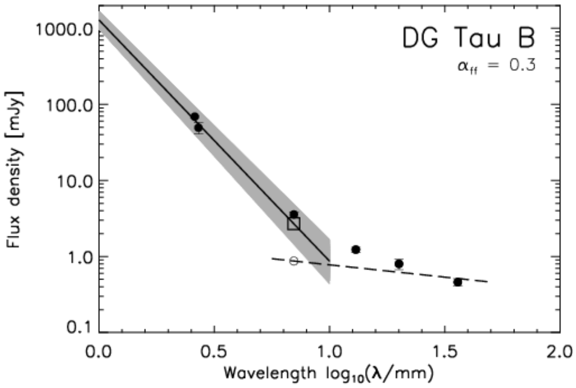

Figure 5. Example spectral energy distribution of a PEBBLES target (Rodmann et al. 2006).

The methodology for basic image analysis is as described by Greaves et al. (2008). The advantage of very high resolution is that disk structures of Solar System-like size are well resolved – in Figure 1 (a factor of 2 worse resolution than in PEBBLES), the inner disk is clearly separated from the bases of the jets and from the proto-planet candidate. We can therefore obtain clean values of the fluxes originating from different sources and construct radial profiles, etc.. This should remove the problem of earlier studies where objects with both disks and jets were seen with these signals blended, requiring careful disentangling via the change in spectral slope (Figure 5). We note that in PEBBLES the dust-to-free-free flux-ratio will be smaller at 5 cm wavelength than in Figure 1. At 7 mm the median free-free contribution to the total flux is 25%, so at 5 cm this integrated wind/jet emission will be ~7 times brighter than the dust (assuming spectral slopes of mid-range-$\nu^{0.5}$ and ν^2 respectively). We thus plan to confirm the flux deconvolution by obtaining EVLA 1.3 cm images (see Related Datasets below) and using e.g. the Sault-Wieringa algorithm within CASA for deconvolution of sources with multiple non-linear spectral indices.

After removal of free-free emission, the two datasets can then be used to map the dust β-indices as a function of position within the disk. The image analysis then leads directly to the measurable quantities listed in the science outcomes – grain sizes, dust mass, surface density profile, etc.. These parameters will be fed into the modelling of each disk in the survey, and an assessment made of which models of planet formation can best explain the observed disk structures. The *science driver* questions listed above will thus be answered using a combination of direct measurables and simulation results.

Modelling and Simulations

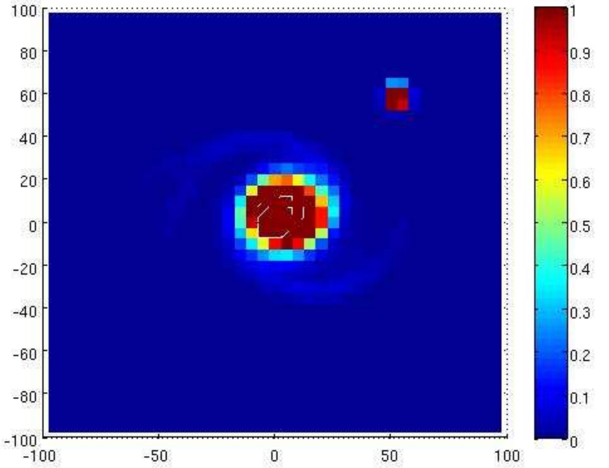

Figure 6. Radio map of the HL Tau disk simulation (Rice, in prep.) showing the overdensity (proto-planet) in the upper right corner and the spiral density waves in the inner disk. The x,y axes are in AU and the pixel size is the 5 AU resolution of eMERLIN at 5 cm. The flux scale is relative; HL Tau b is expected to be ~5 μJy at 5 cm and the accretion (Hill) sphere would be just resolved.

As well as the properties that can be obtained directly from the images, we plan to model each system to test the predictions of different planet-formation theories. We will simulate the evolution of gaseous disks using Smoothed Particle Hydrodynamics (SPH) and have recently implemented a radiation transfer formalism (Forgan et al. 2008) based on a combination of the earlier formalisms developed by Stamatellos et al. (2007) and Mayer et al. (2007). This will allow us to investigate how, for example, the disk mass and surface density profile influence the evolution of the system. It will also allow us to model individual systems to try and match the observations. This has already been done with the HL Tau system (Greaves et al. 2008) where the observations suggest the presence of a bound object in the outer disk and the simulations produce a bound object with a mass and location comparable with that seen in the observations. From the simulations we are also able to produce radio maps to compare with the observations – Figure 6 shows an example from the simulation of the HL Tau disk, at a resolution of 5 AU as it would be seen by eMERLIN at 5 cm. The overdensity identified as a candidate proto-planet and visible in the observations can be clearly seen in the upper right hand corner. The spiral density waves are also visible in the inner disk, but have intensities of only ~ 1μJy/beam. A more massive or non-fragmenting disk may have more visible spiral density waves, especially in the outer disk.

Data Products

From the survey images and matched simulations, we will generate the following survey products:

(a) a catalogue of fundamental disk properties derived from the 5 cm data – dust masses, surface density profiles, and masses and sizes of substructures i.e. proto-planetary clumps, spiral arms and cavities – hence characterising planet-forming potential and linking it to relevant stellar properties;

(b) a catalogue of secondary properties, some in combination with other data – spectral slope of dust continuum (i.e. grain opacity index), inferred largest grain sizes present, disk inclination and orientation, flux contribution of stellar jets and characterisation of structures (e.g. lengths, opening angles), and nature of any background objects (e.g. AGN, see Figure A1 in Appendix);

(c) an atlas of comparative simulations from appropriate models – using the actual disk properties measured (masses, profiles, radii) and known for the host stars (mass, binarity, age) – and a set of conclusions as to which modes of planet-formation operate and in how many disks;

(d) a comparison of the assumed properties of the early Solar Nebula (mass, profile, size of rocky particles, dust opacity) to those measured for the analogue disks, to see if the Sun was exceptional;

(e) the provision of a target list and observation planning information (resolution and sensitivities needed) for future facilities that can image planet-forming disks at other wavelengths – particularly EVLA (for similar resolution at 1.3 cm to eMERLIN at 5 cm), ALMA (to image the spatial distribution of smaller dust grains and molecular gas), and SKA (to map even larger dust at longer wavelengths, up to metre-sized bodies).

Related Datasets

(1) Other Legacy and PI Programmes. PEBBLES is the only project related to planet formation. The programme 'Morphology and time evolution of thermal jets associated with low mass stars' (PI Rodriguez) may have sources in common with PEBBLES, as many of our fields include low-mass protostars and/or Herbig-Haro objects. We would be happy to share any observations that meet the specifications of both projects.

We also intend to propose for **follow-up K-band observations** with eMERLIN in PI time, after obtaining the C-band survey data, in particular to target any proto-terrestrial planets discovered. This is an application unique to eMERLIN, as the 12 mas resolution corresponds to only 1.7 AU diameter at Taurus, so we could image the zone where a *habitable Earth at 1 AU* could form. One Earth-mass of dust has a flux of ~10 μJy at 1.3 cm, so the minimum mass needed to form a low-mass planet could just be detectable with the ~15 μJy rms expected at K-band. Realistically, we would apply for combined eMERLIN+EVLA matched-spectral-configuration observations, for improved sensitivity and coverage of different spatial scales. These follow-up observations are not included in PEBBLES, as the C-band data are needed to first identify the disks with the brightest centrally-concentrated dust.

(2) Complementary data. We plan to also image all of the PEBBLES disks at 1.3 cm wavelength with the **EVLA.** Co-I Chandler will be proposing an Early-Science project for the EVLA which will include observations of proto-planetary disks at 1.3 cm and 7 mm. The resolution of the EVLA in its A-configuration is 80 mas, comparable to the 40 mas of eMERLIN at 5 cm. (We note that eMERLIN has such high resolution at 1.3 cm that the smooth surface brightness of our target disks falls below an achievable rms, so we do not propose it here for PEBBLES.) This combined dataset provides the spectral index information to confirm the reliable separation of the dust and free-free (HII region and jet) emission. The extreme difference in spectral signature (Figure 5) and also in morphology (Figure 1) means that the two sources can be readily separated in well-resolved data. The residual dust fluxes then give the mm-to-cm opacity index of the dust grains and so estimates of their maximum sizes. Data will be shared between PEBBLES and the EVLA Early-Science project for overlapping sources, and a separate proposal will be made to the EVLA for any missing objects needed for PEBBLES science. The EVLA(A-configuration) proposal deadline is expected to be after the date when we will know if PEBBLES is approved.

(3) Other follow-up. Molecular gas contains the bulk of the mass (~99%) initially present in proto-planetary disks, and trace atoms and molecules attuned to a range of densities can be observed via their far-infrared and millimetre transitions. For estimates of the total gas mass, atomic lines such as [OI] are the easiest to interpret, and the majority of our sources are included in **Herschel** Key Projects (GASPS, DIGIT) – these data will be available through Herschel-Co-I colleagues or on public release. Further, we will apply for high-resolution observations with **ALMA**, to image the internal molecular-gas distributions and kinematics of the disks, and detect gas envelopes accreting onto giant planets. When ALMA is fully commissioned, high sensitivity imaging with resolution of ~0.1 arcsec should be routinely available at submillimetre wavelengths, for molecular transitions compatible with the ~100-300 K excitation regime of the inner few AU. PEBBLES Co-I Dent is shortly taking up a Staff Scientist position at ALMA and will be able to co-ordinate these follow-up observations. In the longer-term future, we would like to image even larger dust particles ('boulders') in the disks – theory (Rice et al. 2004) predicts that these bodies are preferentially collected into disk instabilities, so accelerating planet growth. The very weak emission of these boulders is probably generally below e.g. **EVN** sensitivity at 18 cm, but should be possible with **SKA** and/or its pathfinders, e.g. **ASKAP** which is designed to operate longwards of 15 cm wavelength. Imaging planet formation in action is an exciting new area that can help drive SKA science plans.

Technical Case

Summary of Science Requirements

The science goals require resolving different planet-forming zones within the disks and detecting masses of dust comparable to those needed to make planetary cores. With eMERLIN at 5 cm wavelength, the 40 mas beam corresponds to 5-9 AU diameter at the target distances of 140-220 pc, and can thus separate the orbits of the terrestrial and giant planets (Fig. 4, and 7 below). With a detection threshold of 4 mJy/beam (3σ), a compact condensation of dust comprising 5-13 Earth-masses can be detected at the Earth's orbit, equivalent to a super-Earth planet or gas giant core.

Source Regions and Sizes

The sources were selected as described in the science case, based on a mass-ordered list of disks. The 13 target fields include 19 detectable disks within 3 arcmin full-sensitivity fields of view (at C-band and including the Lovell Telescope). Co-ordinates and other details are listed in Table A1 in the Appendix. The target fields lie between RA 03.5h and 05h and Dec. +17 to +31 degrees (the two main nearby young star clusters lie coincidentally in this restricted region of sky).

Mosaicing is not required, but there are two pairs of fields which overlap in their lower-sensitivity outer regions (NGC 1333 IRAS 2/IRAS 4 and L1551/HL Tau: Fig. A1), so assembling a mosaic from these pairs of adjacent pointings may improve image depth for outlying cluster stars. Also, there are three fields with disks spread over ~30 arcsec, where combining three pointings targeting different stars should maximise sensitivity. All disks are compact, e.g. for ~50 AU Solar System-like outer radius, the maximum source diameter is 700 mas when seen at 140 pc, while the region out to Saturn's orbit to which we are mainly sensitive (Table 1) subtends up to 150 mas.

Sensitivities

The calculation of C-band (5 cm) flux for a disk of ≥2.5 times the Minimum Mass Solar Nebula is described in the science case, and predicted flux densities and signal-to-noise ratios are given in Table 1 below. Examples of particular outcomes include the following.

- At the 140 pc distance to the Taurus stars, the *faintest* disks have integrated fluxes of ≥35 μJy for blackbody grains, and even if smooth, can be imaged at ~3σ/beam out to Jupiter's orbit (Table 1).
- For disks that are seen more edge-on, are more massive (Table A1 in the Appendix), or have internal structure associated with planet formation, imaging is possible out to beyond Saturn's orbit (Figure 4) while massive proto-planets can be detect beyond 50 AU (Figure 1).
- For the more distant but slightly more massive disks in NGC 1333 (~220 pc), the surface brightnesses are similar (Table 1) but the planet-forming zones are slightly less well resolved.
- For less efficient grain growth, e.g $\beta = 0.3$, the outer disk regions may not all be detectable, but the Earth/Mars formation zone is detected in *all* the disks, with flux densities of ≥8 μJy (S/N ≥ 6).
- For the central inner-disk region, the per-beam threshold of 4mJy (3σ) corresponds to 2-4 Jupiter-masses of mixed gas and dust at the temperature for the Earth's orbit, or 5-13 Earth-masses of dust within the beam encompassing the terrestrial planet zone.

Figure 7. Sketch of face-on disk seen at 140 pc, with annuli of width equal to the eMERLIN 5 cm resolution. For the furthest disks at ~220 pc (i.e. in NGC 1333), Saturn would appear in the same annulus as Jupiter.

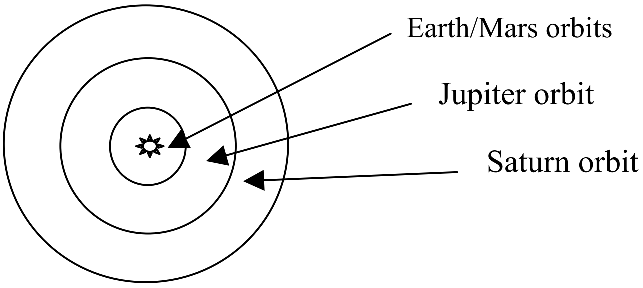

Table 1: Distribution of flux density among planet-forming zones of disks in the survey, assuming they have smooth r^{-1} surface density profiles and are seen face-on; the 40-mas-wide annuli contain 6, 12… beams. For clusters at 140 and 220 pc, the range of disk masses is 2.5-8 and 6-19 MMSN, respectively (Figure 3). An $r^{-1.5}$ disk would be more centrally peaked while inclined disks have higher flux per beam.

distance	annulus (orbital zone)	effective radius (AU)	T_{dust} (K)	M_{ring} (M_{Earth})	F_{beam} (5cm) (μJy/beam)	rms (5cm) (μJy/beam)	S/N_{beam}
140 pc (Taurus)	Earth/Mars	1.5	280	25-80	15-50	1.3	12-35
	Jupiter	5.5	140	50-150	2.5-8	1.3	2-6
	Saturn	11	100	50-150	1-3	1.3	(0.7-2.5)
220 pc (NGC 1333)	Earth/Mars	2	220	100-300	20-60	1.3	15-45
	Jupiter/Saturn	9	110	200-600	4-10	1.3	3-8

Observing Strategy

The observing mode is continuum imaging at C-band with maximum sensitivity, i.e. including the Lovell Telescope – this is essential, as with only half the sensitivity the survey would take ~30% of all the Legacy time. We will observe in wideband (4-8 GHz) continuum mode, as spectral features from the cold molecular disk gas are not expected at these frequencies (ALMA will be used for follow-up gas observations, see above). Overheads for bandpass and primary flux calibration are included in our time estimates, assuming e.g. standard 6+2 minute observations of the science targets and reference sources.

To facilitate the separation of dust and free-free signals, we may choose to observe in two 2-GHz-wide passbands, alternating by frequency switching. A choice of 4.2-6.2 and 5.8-7.8 GHz bands maximises sensitivity while minimising overlap and adding only fractionally more overhead for switching. In this setup, an object with equal dust and free-free flux in the lower-frequency band would have 1.7 times brighter dust in the higher-frequency band, for blackbody and flat spectral indices of the two sources respectively. This mode would be useful for separating disk and wind regions in the images, but is not essential – if frequency switching performed less well than expected, we could revert to single-polarization imaging across a single 4-8 GHz passband.

Time requirements

The rms of 2 μJy/beam per 12-hour track at C-band with the Lovell is assumed to integrate down as $t^{-1/2}$. Thus in three tracks per field, the rms would be 1.2 μJy/beam, or in practice 1.3 μJy/beam (including the time spent on overheads). Our target disks are extended objects and so for the same mass have the *same surface brightnesses*, and are far north enough for full tracks (Table A1), so a uniform 3 tracks per source achieves the *common sensitivity to mass* needed for our science goals.

The **total time required** for the project is thus 13 fields × 3 tracks, i.e. **39 tracks or 468 hours.**

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Data Processing

Pipeline Processing

The pipeline processing for PEBBLES needs to include:

(1) combination of data over 3 tracks per field, with noise integrating down as square-root(time);
(2) maximum sensitivity achieved within central 3 arcmin field of view at 5 cm;
(3) well calibrated visibility data for each whole field;
(4) flux fidelity maintained over a dynamic range of at least 20 and scales of 0.04-1 arcsec.

There are no requirements for polarization information. All observations are continuum imaging of single fields (in a few cases, 2-3 pointings could be advantageously combined)..

The PEBBLES dataset will be ideal for developments of techniques for deconvolving source regions with different spectral indices, i.e. software than can produce images with a spectral index in each pixel. For our targets we expect a clear and well-resolved disk / jet morphology, so our data will provide excellent test-cases for algorithms. The PEBBLES team expects to be able to contribute effort in this area, in collaboration with experts developing algorithms within MIRIAD and CASA, such as Ian Stewart (JB/Radionet), Danielle Fenech (UCL/JB) and graduate student Urvashi Rau (NRAO).

Data Products and Archiving

The primary products will be calibrated 5 cm continuum images, comprising 13 single pointings observed at 1.3 μJy/beam rms over a 3 arcmin field, plus outer fields covering 7 arcmin observed to ~2.5 μJy/beam rms. A minimum of 19 disks is expected to be detected, plus up to 22 further fainter disks within the full-sensitivity fields of view. Other sources within the full fields include 15+ Herbig-Haro objects and 120+ background radio sources (e.g. AGN, star-forming galaxies; for source counts see caption to Figure A1 below). Data products such as source catalogues will be made readily available for reference and for calibration needs of other projects.

All data products generated by the PEBBLES team – images, calibrated visibility data, spectral index maps, flux maps generated from simulations, etc. – will be produced in a commonly used format with adequate metadata. We will ensure compatibility with the Virtual Observatory; Co-I Richards is a VO expert working for Astrogrid. Data products will be archived at a suitable centre; as these are single continuum fields they will not have exceptionally large sizes.

Data Rights

The default 12 months period is suitable for this project.

Management and Resource Plan

Overview: Our team has substantial experience with management of similar-sized projects, e.g. PI Greaves is Survey Manager for SCUBA-2 Legacy Project SUNSS, Co-I's Matthews and Dent are PI's for Herschel Key Projects DEBRIS and GASPS (all on disks); other team members have similar leadership roles. A simple management structure with demarcation of responsibilities by scientific expertise is best for PEBBLES, as the survey strategy requires few in-progress decisions. We have an expert team including nearly *all* the observers world-wide with experience in radio imaging of circumstellar disks, so for simplicity each of the survey fields will be assigned to one expert for reduction and analysis, while the JBO team members will check overall data quality. The sub-teams on complementary data, theory and dust physics are small enough that they can internally co-ordinate according to their expertise. The PI will co-ordinate the overall generation of survey products and management of survey papers.

Team Responsibilities: There are scientists from all the relevant fields (observing, theory, disk physics, dust properties) in the PEBBLES team. The breakdown of main responsibilities is:

Co-ordination: Greaves

Observing planning and data quality: Muxlow, Richards

Data reduction and analysis: Carpenter, Fuller, Hales, Matthews, Mundy, Natta, Richer, Rodmann, Shepherd, Testi, Welch, Wilner

Interpretation and theory: Calvet, Dominik, Dullemond, Merín, Rice, Stamatellos, Ward-Thompson, Wood

Dust experiment / grain physics : Fraser, Henning, Wurm

Complementary observations: Chandler, Dent

Publication: We plan to publish (a) an analysis paper for each target / cluster, within a year after the data are obtained; (b) modelling papers including simulations of all the disks and ~3 overview papers comparing the modes of planet-formation observed to the different models; (c) a main overview paper with catalogues of survey products, within 1 year of final data acquisition; (d) individual interpretation papers e.g. comparison to the Solar Nebula, properties of proto-planets, predictions for ALMA, etc. (e) off-shoot papers with complementary data, new hypotheses, etc..

Decision-making: The survey strategy has been agreed within the whole team, and we do not expect to alter it unless e.g. there is a significant change in eMERLIN capabilities. The division of target fields among the team for reduction and detailed analysis will be by personal interest, such as who has publications or data on an object already. We do not expect internal dispute in the team as there are clear responsibilities and scientific returns for all the people involved, but if there are problems (e.g. paper authorship, delays in tasks) the team will agree a way forward by majority opinion with the co-ordinator having a deciding vote.

Resources: The team currently includes 28 people, based in 6 countries and 17 institutions (6 in the UK). The membership includes 15% PDRA's and we expect to involve several PhD students – present students are not named here simply because data will arrive rather late in their timeframe. We have sufficient effort for the relatively small number of deep single fields we will be observing and modelling, and expect to be able to add to the team, e.g. if the planet-formation PDRA's applied for in the St Andrews/Edinburgh/Strathclyde rolling grant to STFC are approved. Other resources such as computing for simulations and facilities for dust experiment are in place and funded by various national agencies. Most team members have some existing funding for travel to meetings, page charges, etc.. As the team members tend to meet regularly at conferences of mutual interest, PEBBLES meetings (~bi-annually) will be held on these occasions, and interim discussion will be by email, wiki and telecons, as used successfully to formulate the proposal.

Legacy Value

This project is appropriate for Legacy status because it proposes a deep and systematic survey of targets chosen in uniform way; addresses the important scientific question of how planets form; adopts a coherent approach that integrates state-of-the-art observation, theory and experiment by a large international team; and provides targets for future major international facilities.

(A) The science achieved by standard proposals for single or a few favourite disks would be very much less. Radio observations of the faint emission from large grains are difficult, and many papers have studied just one disk (e.g. Table A1). As a result, much was learned about a particular star and its disk but general conclusions about dust growth and the conditions for planet formation could not be made. Notably only two disk-surveys of comparable size to PEBBLES have been published: from 2 mm NRO data for 13 stars by Kitamura et al. (2002) and 7 mm VLA data for 14 stars by Rodmann et al. (2006). Both of these made important advances – the former in showing how disk sizes compare to the Solar System, and the latter in demonstrating that grains do grow efficiently into pebbles in some disks. With a similar systematic approach for PEBBLES involving 19+ disks, we can address even more major questions, at the key wavelengths in the longer radio.

(B) The leap in sensitivity of eMERLIN allows us for the first time to examine the zones where planets form, resolving them in nearby star formation regions and detecting down to a few Earth-masses of dust. No other facility has both capabilities until SKA (ALMA will have high resolution but is not sensitive to the cm-sized grains that are a vital step in forming rocky planetary bodies, and EVLA has insufficient resolution to separate out the terrestrial planet region.) The high-resolution data are the only way to obtain inputs urgently needed for theoretical progress: in particular, the sizes of solid particles, solid-mass reservoir and disk surface density profile on the scales of a few AU that are studied in planet formation simulations and in exo-planet observations.

(C) It is important to take advantage of this unique eMERLIN opportunity with a systematic survey (uniform depth to mass, similar spatial resolutions) – this is the only way to obtain reliable answers to the major unknowns in the field of planet-formation. We pose here a set of science driver questions that can be answered robustly from the imaging results, in conjunction with the best laboratory data on dust particles and grain growth:

(1) *which circumstellar disks proceed to the stage of forming centimetre-sized solid bodies?*
(2) *where does this growth occur within the disks?*
(3) *what mass reservoir is involved, and is planet formation seen to be actually taking place?*

and then by systematic state-of-the-art modelling of systems where we have measured the real observable properties, we can test the basic hypotheses of how planet formation happens: by core accretion, disk instability and oligarchic growth.

(D) In this context, the survey of 19 objects comprises a large sample, in fact nearly half of all the northern stars ever searched for dust emission longwards of 1 mm. In the northern sky, there are only ~150 young stars within 250 pc suitable to study planet formation, and many of these have such low-mass disks that gas giant planets will not be formed. We have therefore adopted a strategy of observing from the most massive disk down to 2.5 times the Minimum Mass Solar Nebula, which is the theoretical boundary for forming planets like the Solar System architecture. This approach of studying the most promising disks is the only way to obtain solid science results within a few hundred hours of observing time and applies strong tests to theory if, for example, dust growth does not occur in the 'best cases'. The moderate-sized sample is large enough to offer robust statistics, if any one system property is vital to success of dust growth into planetesimals.

(E) The database of 19 detailed disk images from PEBBLES will provide targets for future follow-up in the near and long term, e.g. with ALMA and SKA. Observations of very compact proto-planets will always be challenging, and even these powerful facilities will need to observe such objects for long times. The PEBBLES data will provide the best targets – disks with bright dust, strong central peaks and candidate proto-planets – for immediate high-profile science.

Appendix: Target List

Table A1. Properties of the 13 target fields; where other target disks lie in the same 3 arcmin diameter field, these are listed in subsequent lines within the same table cell.
Notes: Evolutionary class FS (flat spectrum) lies between I and II. Optically-invisible objects have no spectral classes. Ages are from Palla & Stahler 2002 (ApJ 581, 1194), Bertout et al. 2007 (A&A 473, l21), Froebrich 2005 (ApJS 156, 169), Testi et al. 1998 (A&AS 133, 81). Cluster distances are 130-150 pc for Taurus, L1551 (Loinard et al. 2007: ApJ 671, 546), 220 pc for NGC 1333 (Cernis 1990: Ap&SS 166, 315).
Additional references for long-mm data: Akeson et al. 1998 (ApJ 505, 358); Anglada et al. 2004 (ApJ 605, L137), Choi et al. 2007 (ApJ 668, L183); Di Francesco et al. 1997 (ApJ 482, 433); Lim & Takakuwa 2006 (ApJ 653, 425); Looney et al. 2000 (ApJ 529, 477) and Piétu et al. 2006 (A&A 460, L43) .

target field	evol. Class	age (Myr)	spectral type	disk mass (MMSN)	F_{5cm} (μJy) for $\beta=0$	other target disks	field centre J2000 RA,Dec
NGC 1333 IRAS2A	0	≤0.3		19	114		03 29 00.0, +31 15 00
	0/I	~0.1		15	92	SVS13B	
	0/I	~0.1		11	69	SVS13C	
	0	≤0.3		9	54	IRAS2B	
	0/I	~0.1		6	36	SVS13A1	
NGC 1333 IRAS4A1	0	≤0.2		10	61		03 29 11.0, +31 13 20
T Tau (N)	II	1	K0	8	120		04 21 59.4, +19 32 06
V892 Tau	Ae	4	A0	7	109		04 18 40.6, +28 19 16
MWC 480	Ae	7	A3	7	107		04 58 46.3, +29 50 37
HL Tau	I	≤0.1		7	97		04 31 38.5, +18 13 58
L1551 IRS5-N	I	~0.3		6	92		04 31 34.1, +18 08 05
	I	~0.3		4.5	67	IRS5-S	
DG Tau	FS	0.5	K7	6	88		04 27 03.5, +26 05 54
	I	0.5		4	61	DG Tau (B)	
RY Tau	II	2	K1	3	47		04 21 57.4, +28 26 35
GG Tau A	II	3	K7	3	46		04 32 30.3, +17 31 35
UZ Tau (E)	II	0.2	M1	2.5	41		04 32 42.9, +25 52 31
HP Tau	FS	6	K3	2.5	41		04 35 52.8, +22 54 23
DO Tau	II	0.6	M0	2.5	37		04 38 28.6, +26 10 50

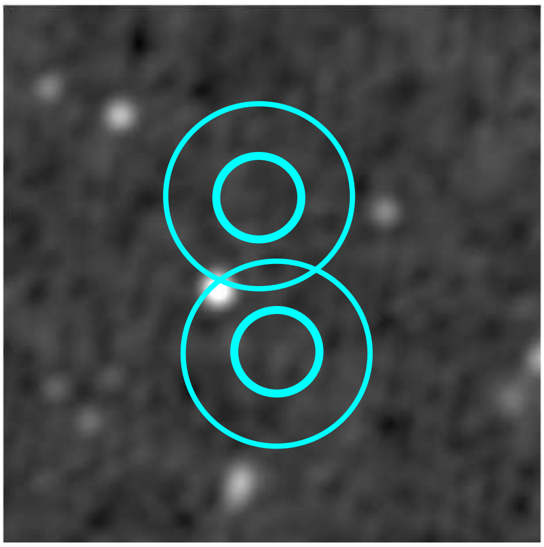

Figure A1. Illustration of low confusion with background sources. Circles of 7, 3 arcmin diameter corresponding to the 5 cm full field and central most sensitive field with the Lovell Telescope, overlaid on the NVSS VLA survey (1.4 GHz, rms ~0.45 mJy: Condon et al. 1988, AJ 115, 1693). The image is 20 arcmin across and shows the HL Tau and L1551-IRS5 fields (upper and lower). At 4-8 GHz, each full field should have ~10 faint background sources (see 5 GHz ultra-deep field, flux limit ~0.13 mJy similar to our median disk flux: Seymour et al. 2008, MNRAS 386, 1695). For the PEBBLES disks subtending <1", the probability of confusion with a background source is <1 in 30,000.