Observational Constraints on Late Heavy Bombardment Episodes around Young Solar Analogs

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ABSTRACT

The excess thermal infrared emission from 36 G and K stars with ages corresponding to the period of Late Heavy Bombardment on the Moon (prior to 3.8 Ga) is estimated. These stars are among 38 selected by analogy to the Sun at an age less than 0.8 Gyr. Measurements or upper limits at 12, 25, and 60 μm wavelengths from observations by the *Infrared Astronomical Satellite (IRAS)* were obtained and photosphere emission subtracted by combining the models of Kurucz with ground-based optical and near-infrared data. A single star, HD 128400, has significant excess emission consistent with dust at a blackbody temperature of 490 K and with an emitting area $\sim 7 \times 10^3$ times that of the present Solar System Zodiacal Cloud. The individual measurements of the remaining 35 stars and their distribution rule out 260 K dust emission at a level exceeding 900 times present Zodiacal. A model for dust production by cometary impactors scaled to the lunar cratering record is used to predict emission at *IRAS* wavelengths and show that dust from Late Heavy Bombardment episodes around these stars would fall below detectable levels after 500 Myr (4.1 Ga). The circumstellar emission from HD 128400 is broadly consistent with the model at the star's predicted 300 Myr age.

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1. Background

Similar crater size/frequency distributions on the lunar and Martian highlands and on Mercury point to an early epoch of bombardment occurring throughout the inner Solar System and distinct from the cratering history on the outer planet satellites (Shoemaker & Wolfe 1982; Woronow, Strom & Gurnis 1982; Strom 1987). The chronology of this event is based on isotopic age-dating of four lunar basins, the youngest of which, Mare Imbrium, has an age of about 3.85 Gyr (Basaltic Volcanism Study Project 1981). This is 0.65 Gyr subsequent to the accretion of the Earth and the formation of the Moon (Lee et al. 1997) and thus this cratering episode is referred to as the Late Heavy Bombardment (LHB). Tectonic resurfacing on the Earth has removed any physical trace of this period, but the relative isotopic abundances of the noble gases (Farley & Neroda 1998), the abundances of terrestrial siderophilic elements (Chyba 1991), and "carbonados", crustal diamond clusters possibly produced by impact shocks (Hough et al. 1995; Daulton & Ozima 1996) may be indirect evidence. Viking and Martian meteorite data also suggest an early bombardment on Mars (Turner et al. 1997; Grady, Wright & Pillinger 1998).

The precise ages of the lunar basins, the duration of the bombardment, and whether it was ubiquitous in the inner Solar System or was confined to the Earth-Moon system are the subjects of ongoing debate (Deutsch & Stöffler 1987; Ryder 1990; Haskin 1998). Nevertheless, the LHB may have profoundly affected the Earth through atmosphere erosion (Melosh & Vickery 1989), the delivery of water (Chyba 1987) and organics (Chyba et al. 1990), and shock-induced atmospheric chemistry (Fegley et al. 1986). The LHB is of fundamental interest in studies of the origin of life because it immediately precedes the oldest evidence for a biosphere (Awramik, Schopf & Walter 1983; Schidlowski 1988; Mojzsis et al. 1996). The LHB may have shaped the environment in which life first arose (Chyba 1993), and limited its earliest persistence (Maher & Stevenson 1988; Sleep et al. 1989).

The potential importance of the LHB to the geochemical and biological history of our own planet compels questions about the frequency and nature of analogous events around other young solar-type stars. Observations of other stars do not, of course, provide direct information on early events in our Solar System. However, such measurements can place the early Solar System and the LHB eon in an astrophysical context. While the detection of Earth-mass planets and planetary impactors is beyond present observational capability, it is plausible that concomitantly elevated levels of interplanetary dust were generated by collisions between impactors and the liberation of volatiles from their surfaces (Anders 1989), and that analogous episodes in other planetary systems would do likewise. LHB dust grains could comprise a minute fraction of the total mass but the majority of the surface area and in principle their thermal infrared emission can be detected. Our own Solar System contains a disk of dust generated by the collision of asteroids (Reach et al. 1997; Durda & Dermott 1997) and the disintegration of comets (Liou, Dermott & Xu 1995). The simultaneous occurence of a spike in the accretion rate of He-3-bearing interplanetary dust particles and several major impacts in the late Eocene (Farley et al. 1998) supports a connection between dust production and impact rate.

Thermal emission from circumstellar particles at 8-100 μm wavelengths was detected around many bright main sequence stars by the *Infrared Astronomical Satellite (IRAS)* (e.g., Aumann *et al.* 1984; Sadakane & Nishida 1986; Walker & Wolstencroft 1988; Stencel & Backman 1991; Mannings & Barlow 1998) and actual dust disks have been resolved around at least four stars (Smith & Terrile 1985; Holland et al. 1997; Koerner et al. 1998; Greaves et al. 1998). While these systemss are interesting in their own right, their connection to conditions around the ancient Sun is not clear. Here I describe a search for circumstellar emission in *IRAS* observations of nearby main sequence stars selected *a priori* for their analogy to the young Sun. The focus on a uniform, rigorously-selected sample of young solar analogs and the use of more sophisticated stellar spectral energy distributions (SEDs) distinguish this effort from previous work. If infrared emission consistent with Late Heavy Bombardment dust formation is observed around many of these stars, one might conclude that bombardment episodes are ubiquitous and long-lived. If such detections are rare, it might suggest that LHB events are brief or that our own Solar System was special in some way.

2. Objects, Observations & Analysis

Thirty-eight young solar analogs were identified based on their proximity ($d < 25$ pc) and their analogy to the predicted characteristics of the Sun prior to 3.8 Ga, i.e., at an age less than 0.8 Gyr. The selection criteria and the catalog are described in detail elsewhere (Gaidos 1998). Briefly, stars were selected based on a bolometric luminosity between 0.43 and 1.10 $L_{\odot}$, i.e., within about 60% of the predicted solar luminosity at 4.2 Ga; a luminosity and effective temperature consistent with the solar metallicity zero-age main sequence; lack of known stellar-mass companions within 800 AU (where tidal effects on an analogous planetary system would be appreciable); and a coronal X-ray luminosity indicative of a level of activity predicted for the Sun prior to 3.8 Ga. These stars were selected from objects in a catalog constructed from photometric and astrometric observations by the *Hipparcos* observatory satellite (Perryman et al. 1997). X-ray flux measurements in the 0.2-2 keV energy range were extracted from the the *ROSAT* Bright Source Catalog (BSC), which contains the brightest sources in the All Sky Survey conducted by the *Roentgen X-ray Satellite* (Trümper 1993; Voges et al. 1996). The spectral types of the young solar analogs range from G0 to K2 (the ancient Sun was a G5 star) and most of the published kinematic measurements and spectroscopy support ages between 0.3 and 0.8 Gyr.

Flux densities (flux per unit frequency) at 12, 25, and 60 μm wavelengths were extracted from source catalogs made from observations by the *Infrared Astronomical Satellite (IRAS)* (Moshir *et al.* 1992). Thirty-six of the young solar analogs have *IRAS* detections at 12 μm. Sixteen of these have detections at 25 μm while the other stars have reported upper limits. Only upper limits are available at 60 μm. The flux densities were corrected for a 5000 K blackbody spectrum (Moshir et al. 1992) and revised the 12 and 25 μm values downwards by 4.1%, 5.7%, respectively, as suggested by Cohen et al. (1996). Ground-based measurements in the 1-5 micron range were obtained from a Catalog of Infrared Observations Version 4.1 (Gezari, Pitts & Schmitz 1993) compiled from the published literature.

The stellar photosphere contribution to each measurement was estimated and subtracted using unweighted least-squares fits of the spectral energy distribution models of Kurucz (1992) to the visible and near-infrared data (if available): The *IRAS* measurements were *not* used in the fitting procedure. The free parameters were the choice of SED and the absolute intensity normalization. (I found the reported spectral types unreliable for choosing SEDs). Kurucz models are available for effective temperatures in increments of 250 K and a range of abundances and surface gravities. The surface gravity of main sequence G stars does not vary significantly. A comparison of SEDs with metallicities (relative to solar) ranging from $\log Z = -0.2$ to $+0.5$, spanning the range of measured abundances of these stars, revealed a variation in the 0.55 μm flux density of only 1%: Variation at longer wavelengths was smaller. I thus exclusively used SEDs with $\log g = +4.5$, solar abundance, and effective temperatures between 4750 and 6000 K. Mid-point interpolations between SEDs were constructed by computing the geometric mean of fluxes from two neighboring SEDs.

The optimal SED was determined on the basis of minimal χ^2 for the eight stars with measurements at multiple (infrared) wavelengths. In the majority of cases where only a single measurement at 0.55 μm is available the SED was chosen by requiring consistency between the photosphere radius from stellar theory (Allen 1978) and that derived from the model absolute flux, measured apparent flux, and the *Hipparcos* parallax. Independent temperature estimates from spectroscopy or photometry are available for 13 stars: The RMS difference between these values and the fit values is 126 K, no larger than the temperature resolution of the suite of SEDs. The Kurucz SEDs reproduce the data to high precision over the 0.5-25 micron range (Fig. 1). The contribution to the error in excess flux density by the uncertainty in choice of SED was taken to be one-fourth the difference in the flux densities between the next warmer and next cooler models.

3. Results

After subtraction of photosphere emission, the residual flux densities were converted to luminosities (per unit frequency) by multiplying by the stellar distance squared. These are shown in Fig. 2 with error bars calculated by adding measurement and modeling errors in quadrature. A crude but convenient means of expressing relative amounts of circumstellar dust is a comparison with blackbody emission from dust at a single temperature and with an emitting area scaled to the Zodiacal emission of the Solar System. I define "one Zody" (1 $\mathcal{Z}$) as the effective emitting area of the Solar System Zodiacal cloud assuming blackbody emission at 260 K (Reach et al. 1996) and a total luminosity of $8 \times 10^{-8} L_{\odot}$ (Good, Hauser & Gautier 1986). I find $1\mathcal{Z} = 5 \times 10^{-6}$ AU^2. While this treatment of Zodiacal emission is unrealistic, the definition is conceptually useful. For example, the effective area of the dust around β Pic with a temperature of about 108 K (Backman & Paresce 1993) is a gargantuan $8 \times 10^6 \mathcal{Z}$. Flux densities from blackbody dust emission were calculated by convolving a Planck spectrum through each of the *IRAS* response curves and making the same corrections as applied to the data.

The G5 star HD 128400 is the sole star which exhibits a detectable infrared excess. This excess was first noted by Oudmaijer *et al.* (1992). The ratio of 12 to 25 μm excess flux densities corresponds to a blackbody temperature of 490 K, in agreement with the 460 K estimated by Oudmaijer et al., and suggests significant amounts of dust within 0.2 AU of the star. The effective emission area is approximately 6600 $\mathcal{Z}$. The predicted blackbody flux density in the 60 μm *IRAS* channel is 0.08 Jy, consistent with the upper limit of 0.14 Jy. The total luminosity (assuming a blackbody) is $6 \times 10^{-3} L_{\odot}$, or 0.9% of the bolometric luminosity of the star. Very little is known about HD 128400 itself: Its Ca II HK emission line strength (Henry et al. 1996) is consistent with its X-ray luminosity and active status. No measurable polarization from dust scattering has been detected (Clarke, Smith & Yudin 1998). I have previously suggested (Gaidos 1998) that its *Hipparcos* proper motion is consistent with the kinematics of the Ursa Major moving group, which has been assigned an age of 300 Myr (Soderblom & Mayor 1993).

The remaining stars have infrared emission consistent with photosphere levels. The strongest limits for circumstellar dust can be placed on κ Ceti, another G5 star with excess 12 and 25 μm luminosities of 0.7 ± 4.7 and -0.6 ± 2.1 Jy-pc^2, i.e., consistent with zero. The two-sigma limits are 10.1, 3.6, and 15.4 Jy-pc^2 at 12, 25, and 60 μm. The 25 μm measurement places a limit of 1600$\mathcal{Z}$ of dust at 260 K (Fig. 1). The equivalent limits for the fainter, more distant stars are a few thousand $\mathcal{Z}$. To constrain the *average* amount of dust around these stars, I calculated a weighted mean 12 μm luminosity of 0.49 ± 1.49 Jy-pc^2, and a mean 25 μm luminosity of 0.11 ± 0.97 Jy-pc^2. The averages are again consistent with zero, and plausible (but not statistically well defined) two-sigma upper limit are 3.47 and 2.05 Jy-pc^2, respectively. The upper limit for the 60 μm band is 23.68 Jy-pc^2. The average amount of 260 K dust around the 15 stars with 25 μm detections is less than 900$\mathcal{Z}$. Furthermore, the χ^2 values for each of the distributions about their respective means are $\chi^2 = 66$ for the thirty-five 12μm measurements, and $\chi^2 = 18$ for the fifteen 25μm measurements. Thus the scatter in the values is consistent with the errors and there is no evidence for intrinsic star-to-star variability. Although the two remaining young solar analogs were not reported in any of the *IRAS* source catalogs, it is *a priori* unlikely that they would have excess emission that would make them more detectable.

One anomalous star (HD 10780) has a 12 μm flux 4 standard deviations *below* the predicted value but still consistent with the 25 μm value. The K0 spectral type agrees with its color ($B - V = 0.81$) and a derived photometric radius of $0.84 R_\odot$. It is the most metal-rich star known in the catalog ($\log_{10} Z = +0.36$), but a high metallicity would tend to produce a *higher* infrared to optical flux ratio. Stellar spottedness, often observed on younger stars, will also increase this ratio. Radial velocity measurements rule out the possibility of a close stellar companion (Tokovinin 1992), leaving this enigma unresolved.

4. A Late Heavy Bombardment Dust Model

Any estimate of dust production during the Late Heavy Bombardment is a perilous exercise since the dynamics of the impactors and the mechanism of dust production is unknown. Futhermore, the lifetime of the dust against orbital decay by Poynting-Robertson drag is short compared to the time scales of interest ($\sim 10^8$ yr) and the amount of dust will be related to the *rate* of bombardment, rather than the *cumulative* number of impacts recorded on Solar System surfaces. With these cautionary caveats, I consider a specific scenario for LHB dust production and scale this to the lunar cratering record to predict the excess infrared emission that would be observed if identical bombardment episodes were occuring around these stars. This model assumes that the impactors were water ice-rich bodies from the outer Solar System region perturbed onto terrestrial planet-crossing orbits (Fernandez & Ip 1983) and that short-period comets are their modern analogs (Levison & Duncan 1997). Other potential mechanisms, including resonance sweeping through the asteroid belt (Gomes 1997), have been suggested.

Each passage of a primeval comet through perihelion is associated with dust release and a finite probability of impact with the Moon. Although perturbations by a giant planet like Jupiter control the residence period of a comet in the inner Solar System (Nakamura & Kurahashi 1998), equation of dust production to number of Earth orbit crossings avoids this complication. I assume that these bodies remain active during their dynamical lifetimes. Water ice sublimation and dust production rates are taken to be proportional to solar insolation and thus to the inverse heliocentric distance squared (Wyckoff 1982). For analytical simplicity, I assume a "dumptruck" release of the integrated dust production at perihelion. Grain orbits decay by Poynting-Robertson drag to heliocentric distances at which temperatures reach 1500 K and the grains are destroyed. Destructive collisions between dust particles are neglected.

The vertical optical depth τ of a collisionless dust cloud, in which local mass production of dust per unit heliocentric distance $Q(a)$ is balanced by Poynting-Robertson transport, is governed by a differential equation independent of grain size distribution;

$$\frac{d\tau}{da} = -\frac{Q(a)c^2}{L_\odot}, \tag{1}$$

where $L_\odot$ is the solar luminosity. If the dust production consists of discrete perihelion releases of mass M from a population of comets passing through perihelion q at a rate $f(q)$, then $Q(a) = Mf(a)$. The prescription $f(q) \sim \sqrt{q}$ in the inner Solar System is justified both by observations (Kresák 1982) and theoretical considerations (Weissman 1985; Ferdández & Ip 1991). The dust mass release is proportional to the amount of water ice sublimated by the integrated solar insolation;

$$M = \frac{DA}{C} \int \frac{L_\odot}{4\pi a(t)^2} dt, \tag{2}$$

where D is the ratio of dust to total mass, A is the effective cross-section of the comet (approximately equal to its physical cross section for low albedo), and C is the heat of sublimation. The integral is evaluated over the period of time when the $a < a_{max}$ and sublimation is occuring (the comet is active). The integral can be expressed in terms of anomaly angles using Kepler's Third Law. A simple solution is available for a population of objects on near-parabolic orbits with a perihelia distribution $\sqrt{q}$ for $0 < q < a_{max}$:

$$M = \frac{2DAL_\odot}{3\pi C\sqrt{2GM_\odot q}} \tag{3}$$

The perihelion distribution can be expressed as $f(q) = f(1AU)\sqrt{q/1AU}$ where $f(1AU) = 3R/(2P)$, P is the lunar impact probability per orbit and R is the lunar cratering rate. Eqn. 1 becomes

$$\frac{d\tau}{da} = -\frac{DARc^2}{\pi PC\sqrt{2GM_\odot} \times 1AU}. \tag{4}$$

The comet cross-section is averaged over the mass distribution of all impactors, while the cratering rate is averaged over all impactors contributing to the count of lunar craters larger than 4 km (Chyba 1991). Taking an impactor mass distribution $n(m) \sim m^{-1.54}$, a crater diameter-mass relation $m^{0.30}$, and a maximum crater diameter of 2200 km (Chyba 1991) I find $\bar{A} \approx 65A_{4km}$. A 140 meter-diameter pure water ice impactor with an encounter velocity of 20 km s^{-1} is capable of forming a 4 km diameter crater. I estimate $P \approx 4 \times 10^{-10}$ using the terrestrial impact probabilities of 14 short-period comets (Olsson-Steel 1987) and correcting for lunar size and gravity. I assume $D = 0.3$ as a plausible but poorly known dust mass fraction. The optical depth of the dust disk is then

$$\tau = \tau_0 \left(a_{max} - a\right) \tag{5}$$

where $\tau_0 = 4\times10^{-5} MyrR$. The current cratering rate due to all *known* short-period comets is 1×10^{-3} Myr^{-1} for the Earth (Olsson-Steel 1987) and 8×10^{-5} yr^{-1} for the Moon (at present, short period comets contribute only a small fraction of the total impactor flux). The predicted dust contribution at 1 AU is 5×10^{-9}, about 6% of the total and consistent with present estimates (Backman 1997).

The evolution of a LHB dust disk is calculated using an empirical relation for the lunar cratering rate derived from Eqn. 1 of Chyba (1991):

$$\tau_0(t) \approx 0.09e^{-(4.6-t)/0.144} \tag{6}$$

where t is the age of the system in Gyr. The time evolution of the *IRAS* 12 μm and 25 μm luminosities of a LHB dust disk using Eqns. 5 and 6 and assuming blackbody grain emission are calculated and plotted in Fig. 2.

The comparison between the model and *IRAS* measurements suggests that Late Heavy Bombardment episodes around these young solar analogs would have been very difficult to detect with *IRAS* if they are older than 500 Myr (equivalent to the model at 4.1 Ga). Many of the stars in the sample could be older than 500 Myr and this could be one explanation for the lack of detectable dust. However, several are kinematic members of the 300 Myr-old Ursa Major cluster (Gaidos 1998). Intriguingly, the infrared emission from HD 128400, a potential analog to the Sun 4.3 Gyr ago, is not unlike that predicted by the model for the the same age. Future observations by the *Wide-Field Infrared Explorer (WIRE)* (Fang et al. 1996) and the *Space Infrared Telescope Facility (SIRTF)* (Werner & Bothwell 1993) will offer sensitivity improvements in excess of an order of magnitude over *IRAS.* Dust detection will then be limited by the 2% accuracy of current stellar atmosphere models (van derBliek et al. 1996). This senstivity corresponds to a dust luminosity of 2 Jy-pc^2 and I predict that dust from Late Heavy Bombardment episodes in their waning stages will be detectable.

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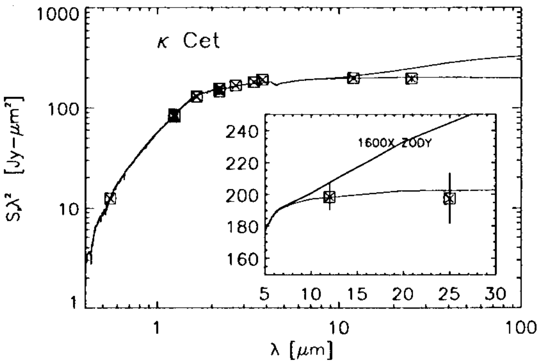

Fig. 1.— Spectral energy distribution of κ Cet with a best-fit Kurucz SED. The RMS deviation of the model from the measurements is 4%. Dust emitting as a 260 K blackbody with 1600× the area of the Solar System Zodiacal Cloud can be excluded by the *IRAS* measurements.

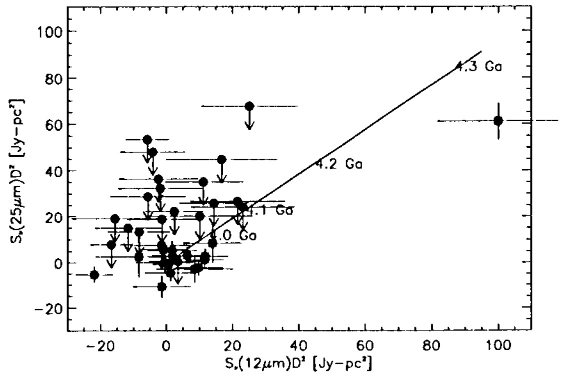

Fig. 2.— Derived measurements or limits on excess 12 and 25 μm emission from 36 young solar analogs. A model of dust production scaled to the lunar cratering record during the Late Heavy Bombardment is plotted.

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