The Galactic Environments of Cool Stars (part I: Modeling Interstellar Dust around the Sun and Nearby Cool Stars)

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Abstract

We present a model of the interaction of interstellar dust grains with a stellar environment, that predicts the distribution of interstellar dust grains in the size range between $0.1 \, \mu m$ and $1 \, \mu m$ around a star for the whole stellar cycle. Comparisons of the model results with in-situ dust measurements by the Ulysses spacecraft in the Solar System validate the model. We show that in the case of the Sun, interstellar dust grains can produce large regions of infrared emission that can be confused with a circum solar dust disk when observed from afar. Our model can determine the shape of interstellar dust concentrations close to nearby stars, if we have information on the relative velocity of the stars with respect to the surrounding interstellar medium, and the properties of the stellar wind.

Introduction

the stellar wind deects interstellar dust grains from their initial direction of motion. The actual direction in which the grains are deected depends on the polarity of the stellar magnetic field and thus on the phase of the stellar cycle. Since the magnetic field produced by the star is usually stronger than the surrounding interstellar magnetic field, the interaction at the heliopause affects smaller grains than the interaction inside the heliosphere. Both interaction mechanisms disturb the ow of interstellar grains around the star. Therefore, interstellar dust density fluctuations can be expected on scales of the stellar atmosphere. This has to be taken into account when infrared observations of the stellar vicinity are analyzed, because spatial disturbances of the interstellar dust distribution can mimic the appearance of circum solar dust disks.

Another aspect of the interaction of interstellar dust with the stellar environment is the erosion of circum solar dust disks by collisions of disk particles with interstellar grains. It has been shown [Liou and Zook, 1999] that the appearance of a dust disk can be a strong indicator of planets that orbit the star. The indicative features of such a dust disk develop on time scales in the order of $10^6$ to $10^7$ years. Depending on the concentration and relative velocity of interstellar dust near the star, these features are eroded before they become strong enough to be detected.

Model description

We simulate the gravity, radiation pressure, and Lorentz-force that interstellar grains experience as they traverse the heliosphere and the Solar System (for a full description see Landgraf [1999]). The relative strength of these forces depends on the grains' size. Grains with sizes below $0.1 \, \mu m$ experience dominantly the Lorentz-force that is created by the solar wind magnetic field sweeping by the grains [Morfill and Grün, 1979]. Since the solar wind magnetic field changes its polarity with the solar cycle, the eect on the spatial grain distribution also depends on the phase of the cycle. Grün et al. [1994] and Gustafson and Lederer [1996] found that during the rst half (1991 to 2002) of the cycle, grains are deected away from the solar equatorial plane, and towards the solar equatorial plane during the second half (2002 to 2013). If the grain size is comparable to the maximum wavelength of the solar spectrum, radiation pressure becomes effective and can even exceed gravity [Gustafson, 1994]. The motion of grains with sizes above $1 \, \mu m$ is dominated by gravity and they approximately move on hyperbolic Kepler orbits.

Simulation results

In Figure 1 we show the spatial distribution of spherical interstellar dust grains with radii of $0.1 \, \mu m$ around the Sun during the whole solar cycle from 1991 to 2013. For this simulation we have assumed an initial relative velocity of the grains of $26 \, \text{km/s}$ with respect to the Sun and a electrostatic grain charge surface-potential of $+5 \, \text{eV}$ [Mukai, 1981]. The figure shows how the spatial distribution of interstellar dust grains around the Sun changes with the 22-year solar cycle. The individual panels in Figure 1 show a rectangular area of $80 \, \text{AU} \times 80 \, \text{AU}$ around the Sun. Figure 4 shows the distribution in the plane that contains the initial dust velocity vector and is perpendicular to the plane that contains the rotation axis and the dust velocity vector. In the case of the Sun, the plane shown in Figure 4 is also close to the solar equatorial plane. During all phases of the solar cycle the solar wind magnetic field repels interstellar dust grains from the vicinity of the Sun.
The average magnetic field strength experienced by a dust grain is higher when the grain is highly ordered during a solar maximum. The first panels show the distribution of interstellar dust grains after they have been concentrated to low heliographic latitudes by a con guration that de estate particles in the northern hemisphere to the south and particles in the southern hemisphere to the north during the 1985 solar maximum. The arc of enhanced particle density downstream of the Sun is generated by the repelling effect of the solar wind magnetic field. Since the average field strength is low during the solar minimum in 1991, the particles propagate freely until they are detected to high heliographic latitudes during the 1997 solar maximum. At this time, the projected solar minimum in 2002 particles are detected to lower heliographic latitudes again, and in 2012 the same distribution is achieved.

Comparison with Spacecraft Measurements

Ulysses has measured a decrease in the ux of interstellar grains after mid-1996 by about a factor of 3. Our model reproduces this decrease, which is due to the de estate phase of the solar wind magnetic field that starts in 1991 and becomes most effective in 1995, according to the model interpretation. Consequently, the spatial concentration of interstellar grains decreases, especially around low heliographic latitudes. Since the grain's charge-to-mass ratio, that controls the coupling of the grain to the magnetic field, is inversely proportional to the grain radius, the smallest grains are affected most by the de estate field. Larger grains are depleted more slowly, due to their inertia. The best agreement with the data is achieved for grain sizes between 0.2 m and 0.3 m, which is also the size range of the most abundant im pactors on the Ulysses dust instrument before mid-1996 (Landgraf et al., 1999). We conclude that the in situ measurements support the model prediction that the distribution of small interstellar dust grains around the Sun is time-independent and changes with the solar cycle.

Prediction of Interstellar Dust around Nearby Stars

Can we predict the spatial distribution of interstellar dust around nearby stars? To model the motion of interstellar dust grains in the vicinity of a nearby star, we need information on the relative velocity of the star with respect to the surrounding medium, the medium's magnetic cycle, and the velocity and the medium's odynamic state of the stellar wind. To assess dust location at the atmospheric boundary region, information on the magnetic field and on the pressure in the surrounding medium is needed.

The Hipparcos catalog contains 1550 stars within 25 pc, of which are G-type stars. The astrometric data can be used to determine the star's velocity. The velocity of the surrounding medium can be determined from absorption line measurements of the nearby interstellar gas (Lallement and Bertin, 1992; Frisch, 1996). The state and periodicity of the stellar wind can be derived from measurements of the stellar mass-loss and activity. Our model is restricted to stars that have a magnetic field orientation similar to the Sun. The motion of very small grains inside an atmosphere cannot easily be modeled if the grain's gyration frequency is in the order of less than the rotation frequency of the star. In the case of the Sun, this is not a strong restriction, because grains with sizes below 0.05 m are limited to the heliopauses region and thus never reach the inner part of the heliosphere.

The result of our model calculations is a three-dimensional distribution of grains around a given star. From this information the grain flux near a circumstellar dust disk as well as the projected distribution of infrared emission can be derived.

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Figure 1. Spatial distribution of interstellar grains with radii of 0.1 m in a 80 AU 80 AU plane that contains the upstream direction vector and is close to the solar equatorial plane. The distribution changes with the solar cycle and is therefore shown as a sequence (from upper left to lower right) of panels that covers the whole cycle from 1991 to 2013.