Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 39 (2007) 413–420
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

Sungrazing comets as solar probes and dust analyzers

W.F. Huebner *, D.C. Boice, N.A. Schwadron

Southwest Research Institute, P.O. Drawer 28510, San Antonio, TX 78228-0510, USA

Received 30 November 2002; received in revised form 20 August 2006; accepted 4 September 2006

Abstract

The largest solar system bodies that approach the Sun closely are comets. Some graze the solar photosphere and are called sungrazers. All of the sungrazing comets undergo disproportionate brightening just before their perihelion passage. This phenomenon and the apparent transformation of the dust tail to a plasma tail have never been investigated thoroughly. Here we investigate fundamental concepts in order to open three new research areas for (1) determining the elemental composition of comet dust, (2) studying the physics of the corona, solar wind, and heliosphere, and (3) developing instruments for high-resolution spectral observations of these phenomena near the Sun. We developed the tools to calculate the correct illumination factors for surface elements and give an analytic solution for the transverse radiation flux when a comet nucleus is close to the Sun.

Keywords: Sungrazing comets; Cometary physics; Cometary dust; Solar corona; Heliosphere

1. Introduction

Since the spectacular apparition of Comet Ikeya-Seki (C/1965 S1), interest in sungrazing comets has steadily mounted. Prior to spacecraft observations, about nine sungrazing comets were known. Since then three spacecraft dedicated to observations of the Sun have detected sungrazers: space-borne coronographs SOLWIND detected six comets (1979–1984) and Solar Maximum Mission (SMM) detected ten comets (1987–1989), respectively. The latest spacecraft, SOHO, has detected in its first ten years of operation since 1996 about 1200 small sungrazing comets (averaging about ten comets per month). Some sungrazing comets, such as Ikeya-Seki (C/1965 S1), survived the close encounter with the Sun while most others like Solwind 1 (C/1979 Ql), which is also known as Comet Howard-Koomen-Michels, did not. They appear to be associated with or possibly even trigger some solar or transient phenomena in the Sun's photosphere that causes observable effects in the solar corona such as the enrichment of heavier elements and light scattering effects (Chochol et al., 1983). All of the sungrazing comets undergo disproportionate brightening just before their perihelion passage (Uzzo et al., 2001). This phenomenon and the apparent vaporization and subsequent ionization of materials in the dust tail to form a plasma tail have never been investigated thoroughly. We investigate here the fundamental concepts in order to open three new methods for (1) determining the elemental composition of comet dust, (2) studying the physics of the corona, solar wind, and heliosphere, and (3) developing instrumentation for high-resolution spectral observations of these phenomena near the Sun.

The composition of comet dust has been investigated in only two comets (Comet 1P/Halley) with the use of spacecraft instruments and the Stardust mission to Comet 81P/Wild 2 by capturing and returning some comet dust particles to Earth for laboratory analysis. If our model for the sudden brightening and the transformation of the dust tail to a plasma tail can be put on a firm physical basis, then dust analysis can be accomplished by remote sensing. Such an investigation would not be based on the analysis of a few dust particles: it would reveal the most comprehensive analysis of the elemental bulk composition of comet dust. Comet nuclei are by mass about 1/3 water ice, 1/3 iron

* Corresponding author. Tel.: +1 210 522 2730; fax: +1 210 543 0052.
E-mail address: whuebner@swri.edu (W.F. Huebner).

0273-1177/$30 © 2007 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2006.09.042

and magnesium silicates, and 1/3 carbon compounds such as CO, CO_2, and hydrocarbon polycondensates (Huebner, 2002). Dust, a combination of silicates and refractory hydrocarbon compounds, is a major constituent of comets.

The largest group of sungrazing comets approaches the Sun from the South of the ecliptic and travels in highly inclined, retrograde orbits ($i \approx 143°$, $e \approx 1.0$, $1/a < 0.01\ \mathrm{AU}^{-1}$ and perihelion distance $q \approx 0.005$ AU) around the Sun as viewed from above the north pole of the solar photospheric disk. They apparently come from the very same direction in space, confined to an area of $0°.8 \times 0°.4$, which is consistent with membership in the Kreutz group. Several other groups of sungrazing comets have been identified: the Meyer group, Marsden group, Kracht group, and possibly (so far only three members) a Kracht II group. Comets in these groups have perihelion distances typically six times larger than the Kreutz group.

In most astronomical applications field quantities such as radiative energy density and flux density are determined from factors of solid geometry in which the distance of the field point from the source is large compared to the linear dimensions of the source, i.e., the source is considered a point source. To investigate sungrazing comets, however, we must determine energy density and energy flux density as a function of angle close to the surface of the Sun. Specifically, we are interested in heliocentric distances $R_\odot < r < 5R_\odot$, where the radius of the Sun $R_\odot = 6.96 \times 10^5$ km $= 0.00465$ AU and a comet nucleus is about 10 km in size. We will start our discussions with the procedure outlined by Ambartsumyan (1958). In this first approximation we assume that the Sun emits radiation uniformly over its surface and ignore limb darkening. Ambartsumyan integrates the radiative intensity from a star (in this case from the Sun) over the angle subtended at a point at a distance r from the center of the star (Sun). This is a reasonable approximation for continuum radiation, but less so for line radiation, particularly if limb darkening is included.

2. The energy density of solar radiation

The brightness of a surface is the amount of radiant energy emitted normal to the surface per units of time, area, and solid angle. When expressed also per unit frequency interval, the radiative intensity at temperature T inside a star is the Planck function

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\left[\exp\left(\frac{h\nu}{kT}\right) - 1\right]^{-1} \quad [\mathrm{J\ m^{-2}\ s^{-1}\ Hz^{-1}\ sr^{-1}}]. \tag{1}$$

If there is no preferential direction for emission, i.e. the radiation is perfectly diffuse, Lambert's law applies

$$B_\nu(\Theta, T) = B_\nu(T) \cdot \cos\Theta, \tag{2}$$

where the angle of emission $\Theta = (\theta + \alpha$, see Fig. 1) toward the very small comet nucleus is measured from the normal

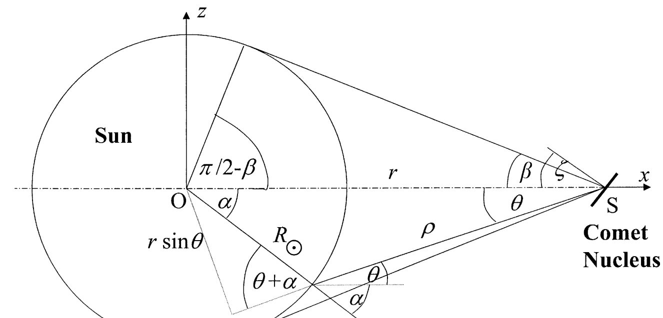

Fig. 1. The solar sphere of radius $R_\odot$ is centered at O. Solar radiation is emitted at angle $\Theta = \theta + \alpha$ relative to the normal, N, of the emitting element on the Sun toward the comet nucleus surface element S, which is at a distance r from the center of the Sun. The normal to surface element S is at angle ζ with respect to the line toward O.

to the surface. The Sun does not emit completely diffusely because cooler layers on the surface of the solar photospheric disk cause limb darkening. However, in the investigation presented here, we ignore the limb darkening effects.

The radiation field of the Sun can be considered sufficiently uniform in time and space so that the radiant energy passing through a surface element will be proportional to the area, the time, and the solid angle of the radiation cone with which an area element intercepts the flux. The total radiative intensity from the surface at temperature T radiated into a hemisphere (solid angle 2π i.e., $\theta = 0$) is

$$\int_0^{2\pi}\int_0^{\pi/2} B_\nu(T) \cdot \cos\alpha \sin\alpha\, d\alpha\, d\phi = \pi B_\nu(T) \quad [\mathrm{J\,m^{-2}\ s^{-1}\ Hz^{-1}}]. \tag{3}$$

The energy density of radiation, which is a scalar, is $1/c$ times the integral over angles of the radiative intensity of the entire emitting surface

$$u_\nu = \frac{1}{c}\int_0^{2\pi}\int_0^{\pi} B_\nu(T)\sin\alpha\, d\alpha\, d\phi = \frac{4}{c}\pi B_\nu(T) \quad [\mathrm{J\,m^{-3}\,Hz^{-1}}]. \tag{4}$$

For the surface of the Sun we will use the measured mean value of the frequency-dependent radiation emittance for the solar disk, πF_ν, in place of $\pi B_\nu(T)$. The total radiation emittance at the Sun's surface is $\pi F = \int_0^\infty \pi F_\nu d\nu = 6.37 \times 10^7\ \mathrm{W\ m^{-2}}$. If we designate the radius of the Sun by $R_\odot$, then for a point above the photosphere of the Sun at a distance $r > R_\odot$ from the center of the Sun

$$u_\nu(r) = \frac{1}{c}\int_0^{2\pi}\int_0^{\beta} F_\nu \sin\theta\, d\theta\, d\phi = \frac{4}{c}\pi F_\nu \frac{1}{2}(1 - \cos\beta), \tag{5}$$

where β is the angle subtended by the Sun at distance r (see Fig. 1) such that

$$\cos\beta = \frac{\sqrt{r^2 - R_\odot^2}}{r} = \sqrt{1 - \frac{R_\odot^2}{r^2}}. \tag{6}$$

Thus, only a spherical cap of the Sun contributes. The energy-density at distance r from the center of the Sun is