SOLAR AND STELLAR WINDS

G. L. WITHBROE
Harvard-Smithsonian Center for Astrophysics
60 Garden Street
Cambridge, MA 02138 U.S.A.

ABSTRACT. This review discusses winds from stars with hot outer atmospheres, stars with coronae similar to the sun. It illustrates how solar observations can be used to test a theoretical model for solar-stellar winds, and thereby provide some insights concerning applications to studying winds from stars other than the sun.

1. Introduction

Because the sun is so close, its outer atmosphere can be studied by a wide variety of techniques not applicable to other stars. The coronal source region of the solar wind can be probed with optical and radio remote sensing techniques and the properties of the asymptotic solar wind can be sampled directly via in situ techniques. Because the solar wind outflow is not spherically symmetric, but originates from magnetically open regions of the solar surface which cover only a fraction of the surface, one can observe solar wind streams which originate in regions with different conditions. Data from different regions provide multiple constraints for testing theoretical wind models for stars with hot coronae.

A type of model which appears to be particularly useful for such stars is the radiative energy balance model, whose properties have been discussed in some detail by Hammer (1982a, 1982b). These models assume that the corona is heated by a mechanism in which the mechanical energy flux F_m responsible for the heating is dissipated with a characteristic dissipation length H_m. The model also assumes that the flux of energy carried by thermal conduction inward toward the stellar surface from the corona is dissipated by radiation in the low corona and chromospheric-coronal transition region. This assumption, along with the solar wind equations for conservation of mass, momentum, and energy, yield a model with two adjustable parameters for a star of known mass and radius. These parameters are F_m and H_m. For solar observations, it necessary to include the effects of non-spherical expansion and the effects of acceleration provided by Alfvén waves (see Holzer 1988, Leer 1988, Withbroe 1988a).

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2. Solar Observations

In situ measurements of the solar wind have been acquired near the ecliptic from 0.3 AU to the outer limits of the solar system. They provide information on electron, proton, and alpha particle temperatures and densities, flow velocities, magnetic field strength and direction, and charge state distributions. There are two classes of steady-state wind, high speed and low speed solar wind, with typical speeds of, respectively, 700 km/s and 350 km/s. High speed wind comes from coronal holes, low density coronal regions with unipolar magnetic fields. Low speed wind appears to come from denser, magnetically complex regions. Optical observations provide measurements of coronal electron densities throughout the corona (broad-band white light measurements made at eclipses and with ground-based and satellite coronagraphs) and information on temperatures, densities, abundances, nonthermal random velocities, and flow velocities near the coronal base (EUV and x-ray instruments), and temperatures, densities, nonthermal random velocities, and flow velocities out to several solar radii (UV coronagraphs). Radio observations provide information on flow velocities by monitoring interplanetary scintillations of natural and artificial sources located beyond the sun. Some optical and radio measurements relevant to solar wind studies are summarized by Withbroe (1988a).

3. Application of Solar Observations to Theoretical Models

Data from different solar regions can be used to evaluate theoretical solar-stellar wind models. Figure 1 shows the radial variation of the electron density N_e, temperature T, and flow velocity V for an equatorial coronal hole. The points are the measurements and the curves the results of model calculations. The solid curve is for the best-fitting thermally driven wind. It predicts flow speeds at large distances from the sun which are too low, a common failing of solar wind models in which the wind is driven solely by thermal pressure gradients. If one includes additional acceleration by waves, most often assumed to be Alfvén waves (which can pass through the dense low corona and deposit their momentum and energy in the supersonic region of the wind), then it is possible to account for the high asymptotic speeds observed. The required Alfvén wave flux is consistent with amplitudes of nonthermal velocities measured in the low corona via the widths of spectral lines.

One can make similar comparisons between parameters measured in other solar regions (see Withbroe 1988a, 1988b and references cited therein). The results indicate that radiative energy balance models provide a good fit to solar data. For coronal holes it appears that the mechanical energy flux at the coronal base $F_m \approx 4 \times 10^5$ erg cm^{-2} s^{-1}, the Alfvén wave flux $F_A \approx 2 \times 10^5$ erg cm^{-2} s^{-1}, and the characteristic dissipation length for the mechanical energy flux is 0.4 to 0.8 $R_\odot$ (and about 0.2 $R_\odot$ in the more dense quiet regions). The mechanical energy flux heating the corona in coronal holes (large scale magnetically open regions) is approximately equal to that in large scale magnetically closed regions, which appear to cover most of the solar disk outside of active regions (which are smaller scale closed structures with much stronger fields).

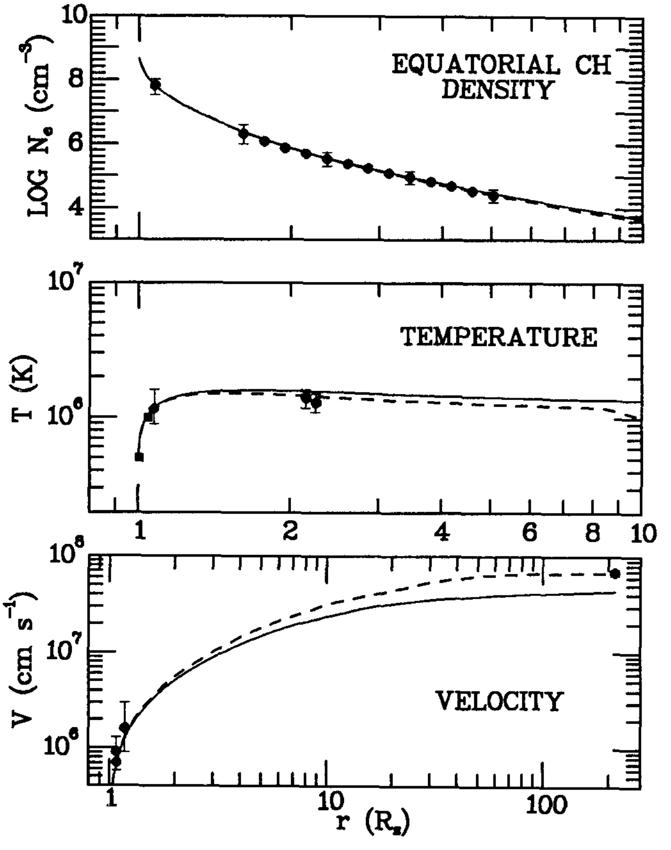

Figure 1. Comparison of empirical densities, temperatures, and flow velocities (points) with those calculated with a radiative energy balance model (curves). The solid curves are for a purely thermally driven wind; the dashed curves show the effect of adding sufficient energy in the form of Alfvén waves to raise the asymptotic flow speed to that observed.

4. Implications for Mass Loss From Stars with Hot Coronae

The solar mass loss is determined by: (1) the fraction of the solar surface which is magnetically open, typically about 20%, and (2) the heating of the coronal plasma which gives rise to a solar wind which appears to be primarily thermally driven in the subsonic region of the wind (where the mass loss is determined, see review by Leer, Holzer, and Fla 1982). To first order, it appears that the effects of Alfvén waves can be ignored in calculating mass losses for stars similar to the sun. Calculations with radiative energy balance models indicate that the stellar mass loss rate (for a spherically symmetric outflow) depends primarily on the mechanical energy input and is insensitive to its dissipation length for dissipation lengths comparable to a stellar radius, as is the case for the sun (see Hammer 1982b, Withbroe 1988a).

These results suggest that for a star with know mass and radius and a thermally driven wind, two parameters are needed to estimate the mass loss rate, the mechanical energy flux F_m and fractional area of the star covered by magnetically open regions. If only F_m is know, an upper limit to the mass flux can be estimated. Determining F_m is difficult due to the fact that coronal fluxes are likely to be dominated by emissions from closed magnetic regions on the star, as is the case for the sun. However, solar observations suggest the F_m has the same magnitude in large scale magnetically open and closed regions (see Withbroe 1988b), hence an estimate of F_m for closed regions (obtained from, for example, observations of the C IV λ1548 or O VI λ1032 flux) should provide a good first order estimate for F_m and the mass loss rate for the open regions. The resulting mass loss rate will be an upper limit (for a thermally driven wind) because (1) of the assumption of spherical symmetry (overestimate by a factor of 5 for the sun) and (2) the possibility that some of the spectral line flux may come from active regions. For some stars it may be possible to determine the contributions of active regions from information on rotational and stellar cycle variations.

For some solar-type stars, deposition of energy/momentum by waves may influence the mass flux (see Holzer 1988, Leer 1988). Measurements of line widths of stellar transition or coronal lines could be used to place an upper limit on the magnitude of the Alfvén wave velocity amplitude, and thereby place constraints on the relative importance of thermal and Alfvén contributions to the energy driving the mass flux.

To summarize, the presently available results suggest that radiative energy balance models provide a good first order solution to the problem of calculating wind models and estimating mass losses for stars with hot solar-type coronae.

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