INFERENCES ABOUT THE HISTORY OF THE SOLAR WIND FROM STELLAR WIND MEASUREMENTS

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ABSTRACT

All coronal stars presumably produce winds analogous to the solar wind, but such winds are too weak to be directly detected with current remote sensing capabilities. However, the existence of these winds can be inferred indirectly via observations of Lyman-α absorption from the interaction regions between the winds and the interstellar medium. This absorption diagnostic has led to the first estimates of mass loss rates for truly solar-like stars. By analyzing how mass loss correlates with stellar age and activity we can infer what the solar wind was like in the past. We discuss various reasons why this is not only of interest to solar/stellar astronomers but is also of vital importance to those who study planetary atmospheres in our solar system.

Key words: stellar winds; astrophysics; planetary atmospheres.

1. INTRODUCTION

One aspect of the solar wind that cannot be studied by simply making observations of the current wind is its long-term variability. We can study what the solar wind is like today, but it is also important to know what it was like in the distant past, and what it will be like in the future. This issue is not only relevant to those who study the Sun and its wind, but it is also very important for planetary researchers, because of the effects the solar wind may have had on planetary atmospheres in the past.

The best way to assess the time-dependence of the solar wind is by observing other stars. By studying the winds of solar-like stars with different ages, we can infer how such winds vary with time, and thereby determine how the solar wind has changed as the Sun has aged. Unfortunately, coronal winds like that of the Sun are very weak and impossible to detect directly. The winds can be detected indirectly, however, thanks to the large interaction regions called “astropheres” that result from the collisions between the stellar winds and the interstellar medium (ISM). These interaction regions contain a population of heated hydrogen atoms that often produce detectable absorption signatures in Lyα spectra of nearby stars from the Hubble Space Telescope (HST). Since the amount of absorption is correlated with the strength of the stellar wind, analyses of the Lyα absorption has resulted in the first mass loss rate measurements for solar-like stars, permitting the estimation of empirical relations between mass loss, age, and activity.

2. THE Lyα DIAGNOSTIC

Fig. 1 shows the HST Lyα spectrum of the very nearby star α Cen B (Linsky & Wood, 1996). The upper solid line is an estimate of the intrinsic Lyα emission line pro-
Figure 2. The α Cen B spectrum (thin solid line) and inferred ISM absorption (dotted line) from Fig. 1. The dashed lines show the blue-side excess Lyα absorption predicted by 4 models of the α Cen atmosphere, assuming 4 different mass loss rates. The 2.0 $M_\odot$ model fits the α Cen spectrum well. From Wood et al. (2001).

Figure 3. Mass loss rates per unit surface area plotted versus stellar X-ray surface fluxes. Filled symbols are for main sequence stars, while open symbols are for evolved stars. A power law has been fitted to the main sequence stars with $\log F_X < 8 \times 10^5$ ergs cm$^{-2}$ s$^{-1}$. From Wood et al. (2005a).

file from the star. Intervening H I gas absorbs much of this Lyα emission, resulting in the very broad absorption line centered at about 1215.61 Å in the figure. Much narrower and weaker absorption is also seen from neutral deuterium (D I) at 1215.27 Å.

Most of the intervening H I and D I between us and the star is interstellar. However, the ISM cannot account for all of the observed H I absorption. When the H I absorption line is forced to have a temperature consistent with the temperature suggested by the width of the D I Lyα absorption, the ISM H I absorption ends up too narrow to fit the data. Thus, Fig. 1 indicates that there is excess H I absorption on both sides of the line that cannot be interstellar. The excess absorption on the blue side of the absorption line is the atmospheric Lyα absorption that we use to detect and study the stellar wind. The excess absorption on the red side of the line is from heated H I gas within our own heliosphere. The primary reason that heliospheric and atmospheric absorption are shifted away from the ISM absorption, but in opposite directions, is that ISM neutrals are decelerated and deflected as they cross the bow shock. From within the heliosphere we see the resulting heliospheric absorption as being redshifted, while from our position outside the atmospheres we see the resulting atmospheric absorption as being blueshifted.

All relevant Lyα spectra obtained by HST have been analyzed to search for detections of heliospheric and/or atmospheric absorption. The current tally is 8 heliospheric detections and 13 atmospheric detections, although 3 of the atmospheric detections are considered marginal (Wood et al., 2005b). The Space Telescope Imaging Spectrograph instrument, which is the source of most of HST’s archival Lyα spectra, failed in 2004 August. This means that additional observations will not be possible in the near future.

The amount of Lyα absorption produced by an atmosphere will depend on the size of the atmosphere and therefore the strength of the stellar wind. Thus, the atmospheric absorption has been used to provide the first estimates of mass loss rates for solar-like cool main sequence stars. This requires the assistance of hydrodynamic models of the atmospheres (e.g., Zank et al., 1996). Detailed description of the modeling process is provided elsewhere (Wood et al., 2001, 2002, 2005a; Wood, 2004), but Fig. 2 shows the atmospheric absorption predicted by four models of the α Cen atmosphere, assuming four different stellar mass loss rates. The model with twice the solar mass loss rate (i.e., $M = 2.0 M_\odot$) fits α Cen’s blue-side excess absorption best. Mass loss rate estimates have been made in this way for all of the atmospheric detections (Wood et al., 2005a).

Since the winds of cool main sequence stars like the Sun arise in their hot coronae, a correlation might be expected between mass loss and coronal properties such as X-ray flux. Thus, mass loss rates (per unit surface area) are plotted versus X-ray surface flux in Fig. 3. For the main sequence stars, mass loss increases with activity for $\log F_X < 8 \times 10^5$ ergs cm$^{-2}$ s$^{-1}$ in a manner consistent with $M \propto F_X^{1.34 \pm 0.18}$ power law relation shown in the figure.

However, this relation does not extend to high activity levels. This may indicate a fundamental change in magnetic field topology as stellar activity is increased. Other evidence exists that may support this interpretation of the truncation of the mass-loss/activity relation. In particular, active stars are often observed to have stable, long-lived polar starspots (Strassmeier, 2002). This is very different from the Sun, for which spots are only observed at low latitudes. One might imagine that polar spots could be indicative of strong dipolar magnetic field that could envelope the entire star and inhibit stellar winds, thereby explaining why the very active stars in Fig. 3 apparently have surprisingly weak winds. The most solar-like of
the stars in the high activity regime in Fig. 3 is ξ Boo, which is actually a binary star (G8 V+K4 V). It is therefore worth noting that high latitude starspots have been detected for ξ Boo A (Toner & Gray, 1988), and Petit et al. (2005) have detected magnetic field structures that are significantly different from solar, including a 40 G global dipole field and an 120 G toroidal field component.

Our primary purpose here is to use the stellar mass loss measurements to infer the mass loss history of the Sun. It is known that stellar activity declines with age, as stellar rotation rates decay. Thus, the mass-loss/activity correlation seen in Fig. 3 implies that mass loss decreases with time for solar-like stars. This can be quantified by combining the power law relation in Fig. 3 with a relation between X-ray flux and age, \( F_X \propto t^{-1.74\pm 0.34} \) (Ayres, 1997), which yields \( M \propto t^{-2.33\pm 0.55} \) (Wood et al., 2005a). Fig. 4 shows what this relation predicts for the mass loss history of the Sun. The truncation of the power law relation in Fig. 3 leads to the mass-loss/age relation in Fig. 4 being truncated as well at about \( t = 0.7 \) Gyr. The plotted location of ξ Boo in Fig 4 indicates what the solar wind may have been like at times earlier than \( t = 0.7 \) Gyr.

3. PLANETARY IMPLICATIONS

There are several ways in which the solar wind may have affected the evolution of planetary atmospheres in our solar system, including that of the Earth (Ribas et al., 2005). One example concerns the solar wind’s possible involvement in the “Faint Young Sun Paradox.” Stellar evolution models indicate that the Sun should have been as much as 30% fainter in the distant past than it is today. This is a robust result based on our understanding of stellar interiors, which has stood the test of time (e.g., Bahcall et al., 2001). However, Sagan & Mullen (1972) point out that this is a problem for planetary geologists. With the young Sun being so much fainter, temperatures on the Earth and Mars should have been much lower, too low in fact to allow liquid water to exist on their surfaces. This contradicts observations that suggest that liquid water did exist on the surfaces of both Earth and Mars 3.8 Gyr ago.

A stronger wind for the young Sun has been proposed as one possible solution to this paradox. The simplest way for the solar wind to solve the problem would be for the wind to significantly reduce the mass of the Sun. In such an instance, the Sun would have been more massive in the past, making it more luminous than standard solar models predict (Guzik et al., 1987). Recent models by Sackmann & Boothroyd (2003) suggest that if the Sun was only a few percent more massive several billions years ago, that would be enough to solve the paradox. The atmospheric mass loss measurements do indeed suggest that the solar wind was stronger in the past (see Fig. 4). In order to see if it was strong enough, Fig. 5 plots the cumulative mass loss of the solar wind as a function of time based on the mass loss evolution law in Fig. 4, where we assume that for \( t < 0.7 \) Gyr the Sun had a mass loss rate within a factor of 2 of the ξ Boo mass loss rate, \( \dot{M} = 5 \dot{M}_\odot \). The figure shows that during its entire history the Sun should have lost no more than 0.2% of its mass. Since this is not enough to have significantly changed the solar luminosity, the solar wind apparently cannot solve the Faint Young Sun Paradox in this manner.

However, a second more indirect mechanism by which a stronger solar wind could have enabled a warmer Earth climate has been proposed, involving the wind’s attenuation of cosmic rays incident on the Earth’s atmosphere. This mechanism relies on apparent correlations between cosmic rays and global temperatures on various timescales (Shaviv, 2003). Such correlations are controversial, but they may support the existence of theoretical cloud formation processes that involve cosmic rays.
Since clouds are generally thought to cool the Earth, in this scenario more cosmic rays should lead to more clouds and a cooler climate. Conversely, if a stronger solar wind reduced the incident cosmic ray flux, the result would be a warmer climate. Shaviv (2003) argues that the mass loss evolution law suggested by the atmospheric measurements implies a sufficiently strong wind in the past that the Earth’s climate would have been significantly warmed by the resulting reduction in cosmic ray flux.

Aside from its possible involvement in the “Faint Young Sun Paradox,” stellar winds can influence planetary atmospheres more directly by the simple process of erosion. We see this effect in the tails of comets, which consist in part of material blown away from the comet by the solar wind. The solar wind is capable of eroding planetary atmospheres in much the same way. Isotopic ratios such as D/H and $^{15}\text{N}/^{14}\text{N}$ are high in the atmospheres of Titan and Mars, for example, strongly indicating that hydrodynamic escape from these atmospheres has in fact been an important physical process in the evolution of these atmospheres (Lammer et al., 2000; Jakosky et al., 1994).

Grießmeier et al. (2004) have applied the mass loss evolution law derived from the atmospheric measurements to stars with detected extrasolar planets, in order to assess how the stellar wind may be affecting those planets. In our own solar system, the solar wind may have measurable impact on the atmospheres of Venus and Titan (Chasefèvre, 1997; Lammer et al., 2000), but the most intriguing case study by far is Mars, since the history of the Martian atmosphere is intimately connected with the history of water and perhaps life on the planet (Lammer et al., 2003). Mars apparently had water on its surface in the distant past and a thicker atmosphere much more conducive to the existence of water (Carr, 1996; Squyres et al., 2004). Solar wind erosion may be responsible for the loss of both the thicker atmosphere and the surface water (Kass & Yung, 1995; Jakosky & Phillips, 2001). The stronger young solar wind suggested by the atmospheric measurements makes it more likely that the solar wind has played a crucial role in the evolution of planetary atmospheres such as that of Mars.

If the solar wind has caused the disappearance of the Martian atmosphere, then why did this not also happen on Earth? The answer likely lies in the Earth’s global magnetic field, which greatly protects our atmosphere from solar wind erosion. Mars apparently once had a global field, but it disappeared at least 3.9 Gyr ago (Acuña et al., 1999), roughly when Mars is believed to have lost most of its atmosphere. Interestingly enough, this roughly corresponds with the time in Fig. 4 when the solar wind strengthened abruptly ($t \approx 0.7$ Gyr) and entered the low activity regime where the power law mass-loss/age relation applies. This combination of an increase in wind strength and the loss of the Martian global magnetic field may have caused the erosion of most of the Martian atmosphere, changing the climate of the planet forever.

ACKNOWLEDGMENTS

Support for this work was provided by NASA grant NNG05GD69G to the University of Colorado.

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