THE SOLAR WIND AND THE SUN IN THE PAST

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(Received 18 February 2006; Accepted in final form 14 July 2006)

Abstract. Exposure to the solar wind can have significant long term consequences for planetary atmospheres, especially for planets such as Mars that are not protected by global magnetospheres. Estimating the effects of solar wind exposure requires knowledge of the history of the solar wind. Much of what we know about the Sun's past behavior is based on inferences from observations of young solar-like stars. Stellar analogs of the weak solar wind cannot be detected directly, but the interaction regions between these winds and the interstellar medium have been detected and used to estimate wind properties. I here review these observations, with emphasis on what they suggest about the history of the solar wind.

Keywords: solar wind, stellar winds, ultraviolet spectroscopy

1. Introduction

On long timescales the solar wind can alter the character of planetary atmospheres in our solar system. Mars is potentially the most dramatic example of this, since there is substantial evidence that Mars lost most of its atmosphere in the distant past (Carr, 1996; Jakosky and Phillips, 2001), and erosion by the solar wind is a leading candidate for the cause of this loss (Luhmann *et al.*, 1992; Perez de Tejada, 1992; Jakosky *et al.*, 1994; Kass and Yung, 1995; Lundin, 2001; Lammer *et al.*, 2003). The lack of a global magnetic field makes the Martian atmosphere more vulnerable to solar wind sputtering processes than Earth's atmosphere, which is largely shielded from the solar wind by a protective magnetosphere. Mars apparently once had a global magnetic field, but it disappeared $\sim$3.9 Gyr ago (Acuña *et al.*, 1999). The thicker Martian atmosphere dissipated not long after (e.g., Jakosky and Phillips, 2001), consistent with the solar wind being the culprit.

In order to theoretically investigate the plausibility of solar wind erosion removing the greater part of the Martian atmosphere, it is necessary to know what the solar wind was like in the distant past when this is believed to have occurred. After all, there is no reason to believe that the young solar wind was identical to the Sun's current wind.

Space Science Reviews (2006) 126: 3–14
DOI: 10.1007/s11214-006-9006-0

2. The Solar Wind and Corona

The solar wind arises within the Sun's hot corona ($T \approx 2 \times 10^6$ K). The heating processes that yield these remarkably high atmospheric temperatures (considering that the Sun's surface temperature is "only" 5800 K) are still not well understood (e.g., Walsh and Ireland, 2003), but there is no doubt that magnetic fields are responsible, meaning that the solar corona is one of many atmospheric phenomena (e.g., sunspots, flares, prominences, etc.) that are controlled by magnetic fields generated in the solar interior. The dynamo mechanism that generates the magnetic field is not fully understood (Ossendrijver, 2003; Charbonneau, 2005), but its origin is widely believed to be near the boundary between the Sun's radiative interior and convective outer regions, roughly 70% of the distance from Sun center to the surface. After their initial generation, the magnetic fields are strengthened by shearing processes induced by the Sun's differential rotation.

Regardless of exactly how the magnetic energy is generated and then converted to thermal energy, wind acceleration models that assume simple thermal expansion from the resulting hot corona reproduce the observed properties of the solar wind surprisingly well (Parker, 1958), although additional acceleration from coronal MHD waves is sometimes invoked to explain the high speed streams that are often observed, especially at high ecliptic latitudes where they are ubiquitous in solar minimum conditions (MacGregor and Charbonneau, 1994; Suzuki, 2004). Coronae are copious producers of X-ray emission, so stellar coronae have been detected and studied by X-ray observations from past satellites such as *Einstein* and *ROSAT*, and currently operating satellites *Chandra* and *XMM-Newton*. These X-ray studies have shown that stellar coronae are a universal property of solar-like stars, but their properties are highly variable (Schmitt and Liefke, 2004). For example, X-ray surface fluxes from solar-like stars have been observed to cover a range from 10^3 – 10^7 ergs cm^{-2} s^{-1}, with the relatively inactive Sun having a rather low value of $10^{4.5}$ ergs cm^{-2} s^{-1}.

Coronal properties are correlated with stellar age and rotation rate (Skumanich, 1972; Pallavicini *et al.*, 1981; Walter, 1982, 1983; Soderblom *et al.*, 1993; Ayres, 1997; Güdel *et al.*, 1997). Qualitatively, these correlations are well understood. Stars are initially formed by the gravitational collapse of interstellar clouds. Conservation of angular momentum during this collapse typically results in very rapid rotation for newly born stars. Rapid rotation enhances the magnetic dynamo and young stars therefore have very active coronae that are bright X-ray sources. In a process called "magnetic braking" the magnetic field of a rotating star drags against the wind flowing from the star. In time this slows the rotation rate, which weakens the magnetic dynamo and lowers the coronal X-ray flux. The bottom line is that young stars are rapid rotators that are coronally very active, while mature stars like the Sun are relatively slow rotators whose coronae are comparatively inactive.

Based on these stellar observations, the solar corona would have been very different ~3.5 Gyr ago when most of the Martian atmosphere is believed to have disappeared. Therefore, there is every reason to believe that the solar wind would have also been quite different as well. However, it is not clear at all whether the more active corona of the young Sun would have produced a stronger or weaker wind. One might naively expect that a more active corona should yield a stronger coronal wind, but this is not necessarily the case. The X-ray fluxes that are commonly used as the measure of coronal activity are associated with closed magnetic field regions, while the solar wind will flow from open field regions. If a more active Sun results in more of the solar surface being covered by closed field regions that crowd out open fields, then the result might actually be a *weaker* solar wind. The current Sun itself provides evidence for such an effect. During the course of the Sun's 11-year activity cycle, it has been found that the solar wind pressure and mass loss rate are slightly lower during the maximum of the cycle when coronal activity is highest, at least in the ecliptic plane (Lazarus and McNutt, 1990). Thus, determining the coronal properties of the young Sun via observations of young stellar coronae is not enough to estimate the properties of the young solar wind.

3. Detecting Solar-like Stellar Winds

3.1. Attempts at Direct Detection

The only way to determine what the solar wind was like in the distant past is to detect and study winds of young, solar-like stars. Unfortunately, detecting analogs for the solar wind around other stars is very difficult. Other types of stellar winds are very easy to detect. The massive, radiation-pressure driven winds of hot stars and the cool, massive winds of red giants and supergiants both produce P Cygni emission line profiles in spectra of these stars, which allows the measurement of wind properties with reasonable precision (Harper *et al.*, 1995; Mullan *et al.*, 1998; Kudritzki and Puls, 2000). However, these are not solar-like stars and these winds are not analogous to the much weaker solar wind, which provides no such spectral diagnostics.

Astronomers have searched for radio emission from nearby stars that could presumably be from a wind, since ionized winds like the Sun should be sources of free-free emission at some level. However, with current radio arrays a solar-like wind around even a very nearby star will only be detected if it has a mass loss rate orders of magnitude higher than the current solar wind, so there have been no clear detections (Brown *et al.*, 1990; Lim *et al.*, 1996; Gaidos *et al.*, 2000). Claims of very high mass loss rates for a few very active stars based on radio detections have been met with skepticism, as the detected emission is more likely to be from the stellar corona rather than from a wind (Mullan *et al.*, 1992; Lim and White, 1996; van den Oord and Doyle, 1997).

Another novel technique that has been used to search for winds is via X-ray emission. Charge exchange between an outflowing ionized wind and inflowing interstellar neutral atoms should yield X-ray emission in the same way that charge exchange with the solar wind leads to X-rays from comets and planets (Lisse *et al.*, 2001; Cravens, 2002; Dennerl, 2002; Gunell *et al.*, 2004). However, though potentially more sensitive than the radio technique, initial attempts to detect circumstellar wind-induced X-ray emission around nearby stars have not been successful (Wargelin and Drake, 2002).

3.2. Stellar Astrospheres

The only clear detections of coronal stellar winds like that of the Sun are not of the winds themselves, but rather detections of the interaction regions between the winds and the interstellar medium (ISM), which are called "astrospheres," analogous to the "heliosphere" that surrounds the Sun. Models of the solar wind/ISM interaction began soon after the discovery of the solar wind (Parker, 1961). Recent reviews of heliospheric modeling efforts include Holzer (1989), Baranov (1990), and Zank (1999). The large scale structure of the heliosphere is defined by three boundaries. Moving outwards from the Sun they are the termination shock (TS), where the solar wind is slowed to subsonic speeds, the heliopause (HP), where the solar wind and ISM plasma are deflected away from each other, and finally the bow shock (BS), where the interstellar wind flow is decelerated to subsonic velocities. The location of the first of these boundaries was recently established when *Voyager 1* crossed the TS at a distance of 94 AU from the Sun (Stone *et al.*, 2005). The upwind (relative to the ISM flow) directions to the HP and BS are not known observationally, but models place them at distances of about $\sim$140 AU and $\sim$240 AU, respectively.

The ISM immediately surrounding the Sun is only partially ionized. In the wind/ISM collision, the neutral atoms in the ISM do not interact as strongly as the ions, but they still take part through charge exchange. Modeling neutrals in the heliosphere is not easy because the charge exchange sends them entirely out of thermal and ionization equilibrium. Nevertheless, many modern heliospheric modeling codes have become sufficiently sophisticated to properly model the neutrals (Baranov and Malama, 1993, 1995; Zank *et al.*, 1996). These models predict that the heliosphere will be permeated by a population of hot hydrogen atoms (H I), especially between the HP and BS where the interstellar H I is decelerated, compressed, and heated. This region in the outermost heliosphere has been called the "hydrogen wall."

This hot H I, particularly in the hydrogen wall, produces a detectable absorption signature in UV spectra of the H I Lyman-α lines of nearby stars from the *Hubble Space Telescope* (HST). However, the lines of sight to these nearby stars not only pass through our heliosphere, but they also pass through the astrospheres of the observed stars. Thus, it is also possible to detect astrospheric Lyman-α absorption, and thereby indirectly detect solar-like stellar winds.

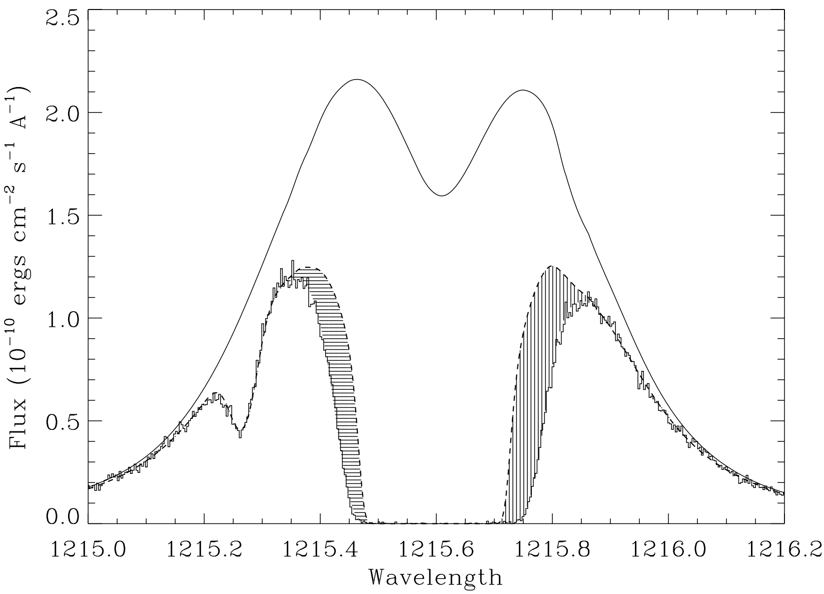

Figure 1. HST Lyman-α spectrum of α Cen B, showing broad H I absorption at 1215.6 Å and D I absorption at 1215.25 Å. The upper solid line is the assumed stellar emission profile and the dashed line is the ISM absorption alone. The excess absorption is due to heliospheric H I (vertical lines) and astrospheric H I (horizontal lines). From Linsky and Wood (1996).

Figure 1 shows the HST Lyman-α spectrum of the very nearby star α Cen B (Linsky and Wood, 1996). The upper solid line is an estimate of the intrinsic Lyman-α emission line profile from the star. Intervening H I gas between HST and the star absorbs much of this Lyman-α 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, but the ISM cannot account for all of the 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 Lyman-α absorption, the ISM H I absorption ends up too narrow to fit the data. Thus, Figure 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 (i.e., short-wavelength) side of the absorption line is the astrospheric Lyman-α absorption signature, and the excess absorption on the red (i.e., long-wavelength) side of the line is from our own heliosphere. The primary reason that heliospheric and astrospheric absorption are shifted away from the ISM absorption, but in opposite directions, is that ISM neutrals are decelerated and deflected as they cross the BS. From within the heliosphere we see the resulting heliospheric absorption as being redshifted, while from our position outside the astrospheres we see the resulting astrospheric absorption as being blueshifted.

Many HST Lyman-α observations of solar-like stars have been analyzed to identify those with detectable heliospheric and/or astrospheric absorption (Linsky and Wood, 1996; Wood *et al.*, 1996, 2005b; Dring *et al.*, 1997; Wood and Linsky, 1998; Izmodenov *et al.*, 1999). Even though all observed lines of sight will pass through the heliosphere and the astrosphere of the observed star, the absorption signatures of these structures are not always detectable. The most common reason for a non-detection is a high ISM H I column density, which leads to broad ISM Lyman-α absorption that obscures the heliospheric/astrospheric absorption. Another factor is the orientation of the line of sight with respect to the upwind direction of the ISM flow. Heliospheric absorption is found observationally to be significantly easier to detect in upwind directions, consistent with model predictions (Wood *et al.*, 2005b). A final major factor that applies solely to astrospheric detectability is the nature of the ISM surrounding the star. Although neutrals are present in the ISM around the Sun, many regions in the "Local Bubble" where the Sun is located will be fully ionized, meaning that an astrosphere in such a location will contain no neutral H to produce Lyman-α absorption.

4. Wind Measurements from Astrospheric Absorption

The current tally of observed lines of sight with detections of heliospheric and astrospheric absorption is 8 and 13, respectively (Wood *et al.*, 2005b). The heliospheric detections are useful for testing heliospheric models and constraining local ISM properties, but we are here more interested in the astrospheric detections, since they represent indirect detections of the coronal winds of these stars. A stronger stellar wind will result in a larger astrosphere and higher hydrogen wall column densities. Thus, a stronger stellar wind will yield more astrospheric Lyman-α absorption, indicating how stellar mass loss rates can be estimated for the stars with detected absorption.

Extracting a stellar mass loss rate from the Lyman-α data requires the assistance of hydrodynamic models of the astrosphere, using the same codes used to model our heliosphere. Models are computed assuming different stellar wind densities, corresponding to different mass loss rates, and the Lyman-α absorption predicted by these models is compared with the data to see which best matches the observed astrospheric absorption. Figure 2 shows the astrospheric absorption predicted by four models of the α Cen astrosphere, assuming four different stellar mass loss rates. The model with twice the solar mass loss rate (i.e., $\dot{M} = 2.0\,\dot{M}_{\odot}$) fits α Cen's blue-side excess absorption best (Wood *et al.*, 2001). Mass loss rate estimates have been made in this way for all of the astrospheric detections (Wood *et al.*, 2002, 2005a). Uncertainties in these mass loss rates are probably of order a factor of two, mostly due to uncertainties in the stellar wind speeds.

The mass loss measurements assume that all coronal winds have velocities similar to the $V_w \sim 400$ km s^{-1} speed of the slow solar wind. Astrospheric size

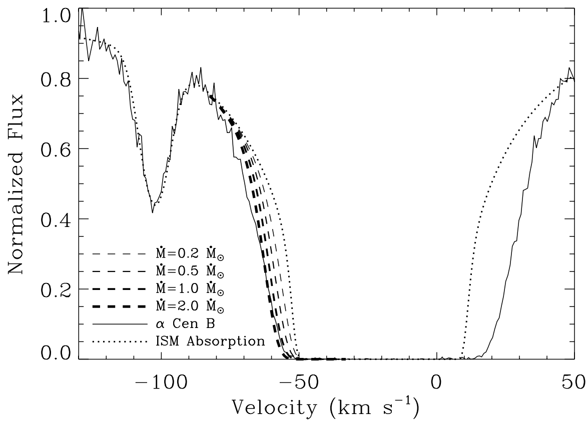

Figure 2. The α Cen B spectrum (thin solid line) and inferred ISM absorption (dotted line) from Figure 1. The dashed lines show the blue-side excess Lyman-α absorption predicted by 4 models of the α Cen astrosphere, assuming 4 different mass loss rates. The 2.0 $\dot{M}_{\odot}$ model fits the α Cen spectrum well. From Wood *et al.* (2001).

and the amount of astrospheric absorption should scale roughly as the square root of the wind ram pressure, $P_w \propto \dot{M} V_w$. If ram pressure was the quantity we were after, to first order the inferred pressure would be independent of the assumed wind velocity. But for many astrophysical purposes the mass loss rate is of more interest. That will be the quantity focused on here, but as a consequence it must be noted that mass loss rates derived from astrospheric absorption will vary inversely with the assumed stellar wind speed (Wood and Linsky, 1998). A justification for the assumption of constant wind speed among solar-like stars is that all cool main sequence stars have roughly the same surface escape speed, and stellar winds of *all* types are generally found to be within a factor of 2 of the surface escape speed.

With these caveats aside, Figure 3 shows mass loss rates (per unit surface area) plotted versus coronal X-ray surface flux (Wood *et al.*, 2005a). For the low-activity main sequence stars, mass loss increases with activity in a manner consistent with the $\dot{M} \propto F_X^{1.34\pm0.18}$ power law relation shown in the figure. The three evolved giant or subgiant stars in the figure do not have mass loss rates consistent with those of the main sequence stars.

It was noted in Section 2 that during the solar activity cycle, the solar wind actually *weakens* slightly at solar maximum, seemingly in contradiction with the apparent mass-loss/activity correlation seen in Figure 3. However, the solar wind is more associated with the large scale dipole component of the magnetic field instead of the small scale active regions responsible for most of the Sun's X-ray emission. The dipole field actually weakens at solar maximum along with the wind. However, the interior magnetic dynamo is ultimately responsible for both the small scale and large scale fields. Thus, it is not unreasonable to expect *both* field components to increase with increasing dynamo activity, at least when averaged over any activity

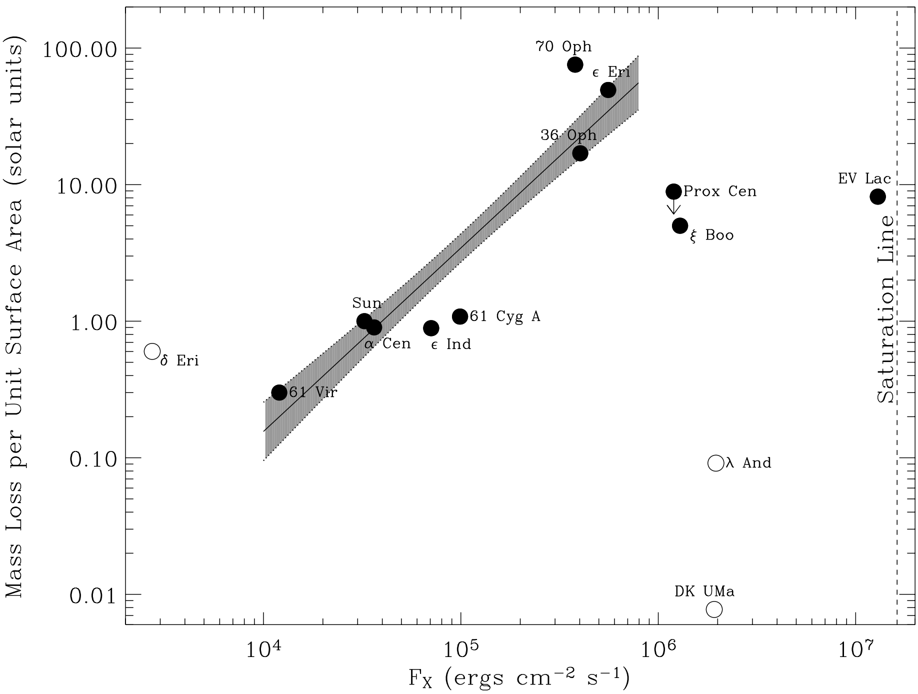

Figure 3. Mass loss rates per unit surface area plotted versus stellar X-ray surface fluxes. Filled symbols are for main sequence stars, while open symbols are for evolved stars. A power law has been fitted to the main sequence stars with $F_X < 8 \times 10^5$ ergs cm^{-2} s^{-1}. From Wood *et al.*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

cycles (Schrijver *et al.*, 2003). In this sense, the correlation in Figure 3 is not surprising, and not in contradiction with the solar cycle behavior.

The mass-loss/activity relation in Figure 3 does not seem to extend to high activity levels. This may indicate a fundamental change in magnetic field topology as stellar activity is increased. Such a change is also suggested by observational evidence that very active stars usually have stable, long-lived polar starspots (Strassmeier, 2002), in contrast to the solar example where sunspots are only observed at low latitudes. Perhaps the polar spots are indicative of a particularly strong dipolar magnetic field that envelopes the entire star and inhibits stellar wind flow, thereby explaining why the very active stars in Figure 3 apparently have surprisingly weak winds. The most solar-like of the stars in the high activity regime in Figure 3 is ξ Boo, which is actually a binary (G8 V + K4 V). It is therefore worth noting that high latitude starspots have been detected for ξ Boo A (Toner and Gray, 1988). Furthermore, Petit *et al.* (2005) have detected magnetic field structures that are significantly different from solar, including a 40 G global dipole field and a 120 G toroidal field component.

Recalling that young stars are more active than old stars (see Section 2), the correlation between mass loss and activity indicated in Figure 3 implies an anticorrelation

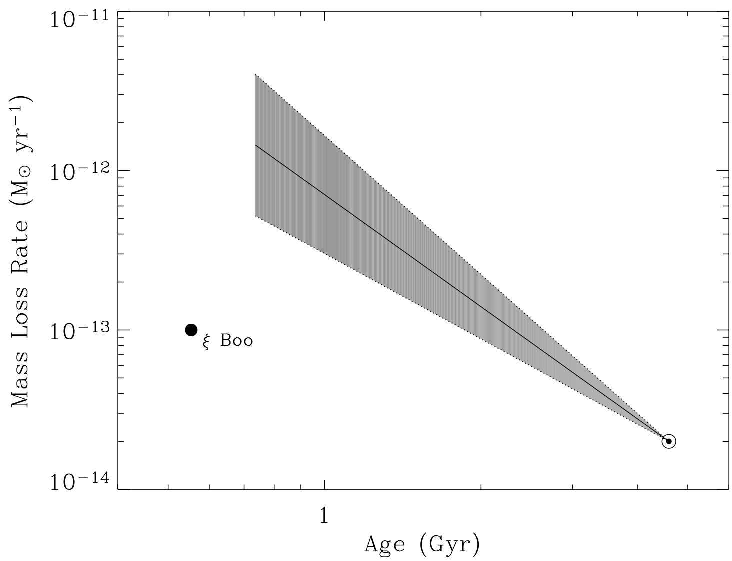

Figure 4. The mass loss history of the Sun inferred from the power law relation in Figure 3. The truncation of the relation in Figure 3 means that the mass-loss/age relation is truncated as well. The low mass loss measurement for ξ Boo suggests that the wind weakens at $t \approx 0.7$ Gyr as one goes back in time. From Wood *et al.* (2005a).

of mass loss with age. Ayres (1997) finds the following relation between stellar X-ray flux and age: $F_X \propto t^{-1.74\pm0.34}$. Combining this with the power law relation from Figure 3 yields the following relation between X-ray flux and age: $\dot{M} \propto t^{-2.33\pm0.55}$ (Wood *et al.*, 2005a). Figure 4 shows what this relation suggests for the history of the solar wind. The truncation of the power law relation in Figure 3 leads to the mass-loss/age relation in Figure 4 being truncated as well at about $t = 0.7$ Gyr. The plotted location of ξ Boo in Figure 4 indicates what the solar wind may have been like at times earlier than $t = 0.7$ Gyr.

The magnetic braking mechanism that slows stellar rotation with time relies on the drag of the magnetic field against the stellar wind, so the time dependence of the wind suggested by Figure 4 has important ramifications for the angular momentum evolution of solar-like stars. These implications are explored in more detail by Wood *et al.* (2002). One interesting result is that theoretical descriptions of magnetic braking are consistent with $\dot{M} \propto t^{-2.33\pm0.55}$ only if disk-averaged stellar magnetic fields decrease at least inversely with age.

5. Planetary Implications

The stellar wind measurements suggest that the mass loss rate of the solar wind was generally higher in the distant past. Analyses of lunar surface soils have also suggested a stronger solar wind in the past, though quantifying the effect is difficult from such data (e.g., Geiss, 1974). This potentially makes the solar wind an even more important factor in the evolution of planetary atmospheres in our solar system. For example, when Mars lost its global magnetic field ∼3.9 Gyr ago (i.e., t = 0.7 Gyr in Figure 4), the Martian atmosphere would have been exposed to a solar mass loss rate about 80 times higher than today, which makes the solar wind a more likely cause of the disappearance of much of the Martian atmosphere. It is interesting that the time when Mars lost its global magnetosphere is also near the time when the astrospheric data suggest that the solar wind strengthened abruptly (at $t \approx 0.7$ Gyr), entering the low activity regime where the power law mass-loss/age relation applies. The poor Martian atmosphere was therefore doubly unlucky. First its protective magnetosphere disappears and at about the same time the eroding solar wind strengthens significantly.

Other atmospheres within the solar system besides Mars may have also been significantly affected by the solar wind, especially Venus and Titan (Chassefière, 1997; Lammer *et al.*, 2000). Wind erosion is also potentially important for many of the extrasolar planets that have been detected around other stars, especially since most of the planets that have been discovered so far are very close to their stars (Grießmeier *et al.*, 2004).

In addition to its eroding effects, a strong young solar wind has also been proposed as a solution for the so-called "Faint Young Sun Paradox." The paradox arises from solar evolution models that suggest the Sun would have been as much as 30% fainter in the distant past, making it difficult to explain why the climates of Earth and Mars were not correspondingly colder (Sagan and Mullen, 1972). It has been pointed out that if the young solar wind were sufficiently strong to significantly lower the mass of the Sun, then the young Sun would have been more massive in the past and therefore more luminous, thereby eliminating the "faint young Sun" (Guzik *et al.*, 1983; Sackmann and Boothroyd, 2003). Unfortunately, though the astrospheric measurements do suggest higher mass loss rates for the young solar wind (see Figure 4), the wind is still not strong enough to have lowered the Sun's mass significantly (Wood *et al.*, 2002). Thus, this solution to the faint young Sun problem is not supported by the data. It has also been proposed that a strong solar wind could lead to a warmer Earth by attenuating cosmic ray inflow into the Earth's upper atmosphere (Shaviv, 2003). However, this proposal relies on controversial claims of a correlation between cosmic ray flux and global temperature.

Before concluding, it should be said that inferences about the history of the solar wind from stellar astrospheric observations would certainly benefit from more data. The mass-loss/activity and mass-loss/age relations presented here are based on only a handful of astrospheric detections. More detections would be especially desirable at high activity levels to better determine what the solar wind was like when the Sun was very young and active. However, the Space Telescope Imaging Spectrograph (STIS) instrument on HST, which is the source of most of the Lyman-α spectra used to detect the astrospheres, failed in 2004 August. This means that additional observations will not be possible in the near future, unless STIS is repaired.

Acknowledgements

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

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