Analysis of stellar winds of solar-like stars with the JVLA and ALMA to define mass loss rates for the young Sun

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Abstract

A warm climate on the young Earth 4 Gyr ago was essential for the formation and evolution of life on our planet. Solar standard models however predict a lower solar luminosity than at present. If the Earth had no atmosphere its temperature would have been 235 K only, while present-day greenhouse gases would raise the temperature to ~253 K, which is still too cold to defrost the entire surface.
To solve this so called "Faint Young Sun Paradox", an *astrophysical* hypothesis has been proposed (Sackmann and Boothroyd, 2003 and references therein). It assumes that the Sun was brighter than according to the standard models, which would be possible if the Sun had been more massive than today. Consequently, a higher mass loss rate driven by the solar wind would have occurred. For an estimate of the enhanced young solar wind, we are trying to detect the free-free emission radio flux of young solar analogs on the main sequence to determine a mass loss rate or upper limits. We use the Karl G. Jansky Very Large Array (JVLA) and the Atacama Large Millimeter/submillimeter Array (ALMA).

Introduction

From climate predictions the initial solar mass would be required to be in the range of 1.03-1.07 M_{sun}, thus suggesting an enhanced early wind mass loss rate of order 10^{-12} – 10^{-10} M_{sun} yr^{-1} (Sackmann and Boothroyd, 2003). The present-day solar wind carries away only about $2x10^{-14}$ M_{sun} yr^{-1} .

Lyman-α absorption

The most productive way to observe these winds uses Lyman-α absorption in high-resolution Hubble Space Telescope spectra (Wood et al., 2005). This method indicates increasing mass loss with decreasing age, which is, however, still not sufficient to solve the FYSP. The scaling is however not well established for the most active stars with near-ZAMS ages.

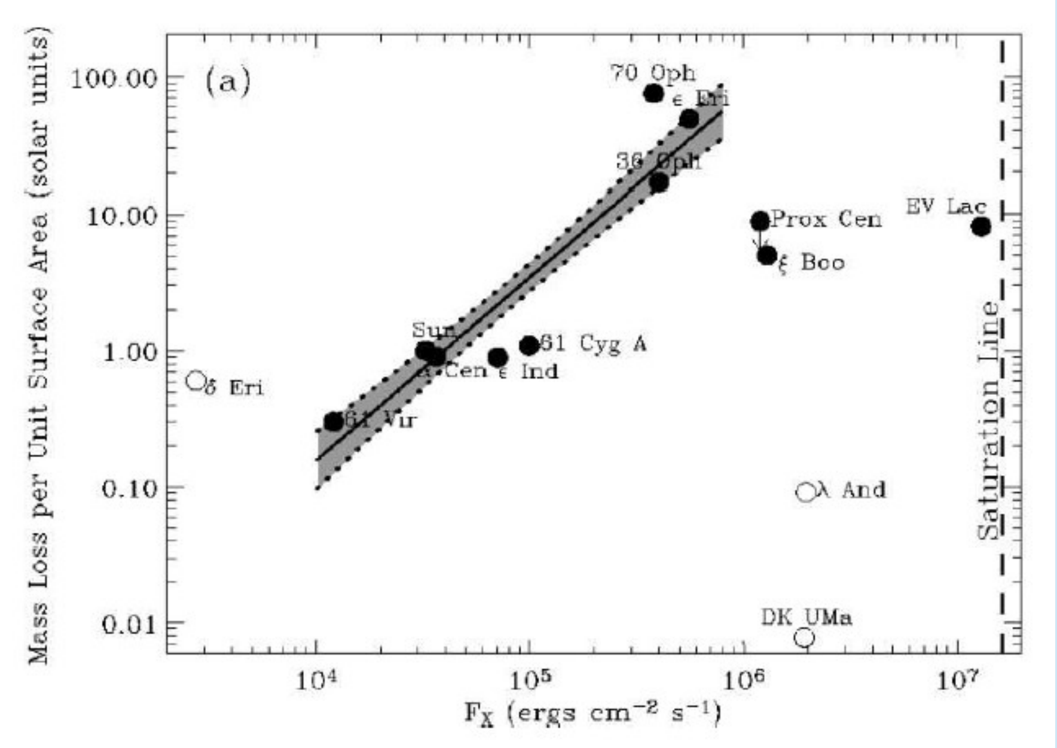


Fig.1: Mass loss rate per unit surface area vs. stellar X-ray flux inferred indirectly from Lyman-α analysis. Main-sequence stars are shown by filled circles, the open circles are evolved stars. The trend for inactive stars (shaded area) is not followed by very active stars (Wood et al., 2005).

Our method to observe stellar winds

We use the JVLA and ALMA to attempt measuring bremsstrahlung (free-free emission) emitted by an ionized wind. Young, active stars feature extensive active polar regions. We therefore study conical winds ejected in polar direction. Gaidos et al. (2000) presented radio observations of solar analogs but did not detect a stellar wind, allowing them to report meaningful upper limits for $\dot{M}$ (~ $1.06\,\dot{M}_{sun}$ for isotropic winds).

The radio flux from a stationary, optically thick, anisotropic (conical), ionized wind is (Reynolds, 1986):

$$S_{\nu}=5.1\cdot 10^{9}\,\dot{M}_{-10}^{4/3}\,v_{400}^{-4/3}\,T_{6}^{0.1}\,d_{pc}^{-2}\,\nu_{GHz}^{0.6}\cdot\sin\left(i\right)^{1/3}/\theta \quad mJy$$

where T_6 is the wind temperature in 10^6 K, d_{pc} is the stellar distance in pc, $\dot{M}_{-10}$ is in 10^{-10} M_{sun} yr^{-1}, v_{400} is the wind velocity in units of 400 km s^{-1}, ν_{GHz} is the observing frequency in GHz, *i* is the stellar inclination and θ is the opening angle of the polar wind in radians.

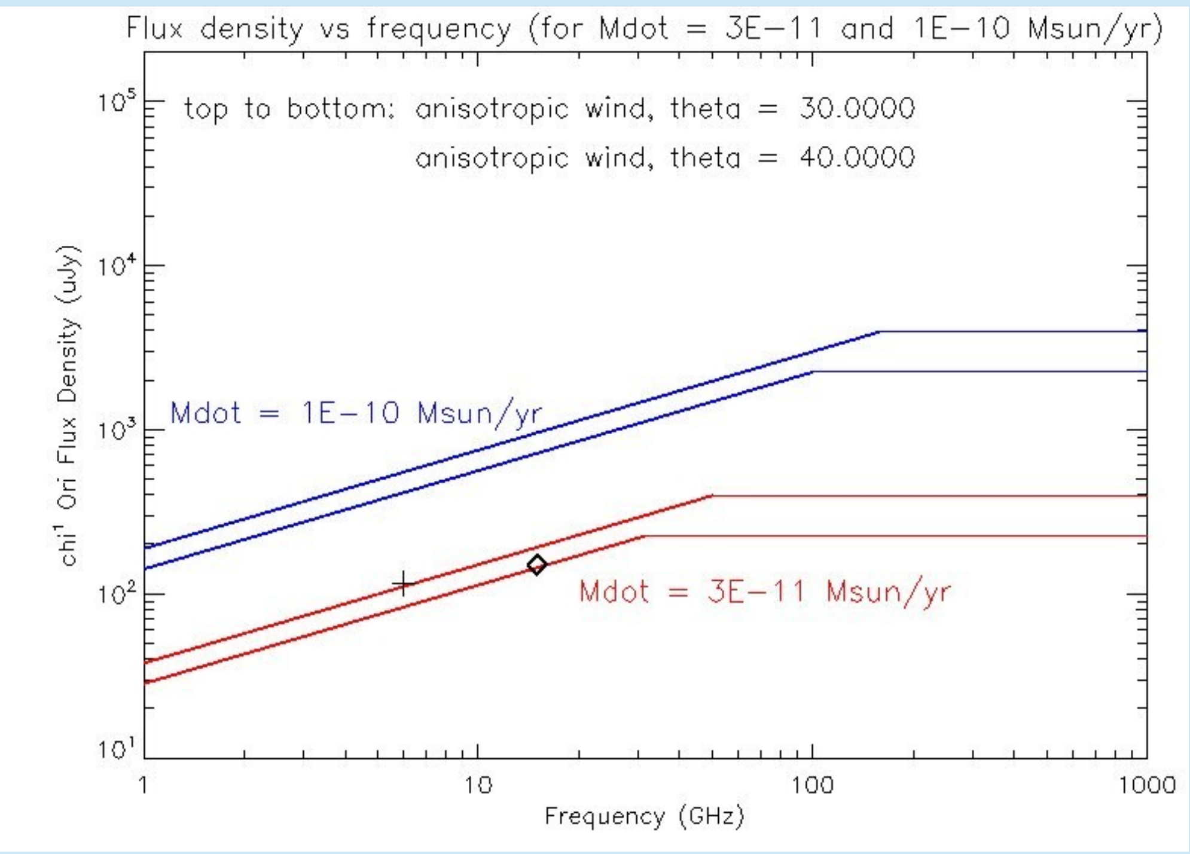


Fig.2: Radio flux from an anisotropic polar wind for a total mass loss rate of $\dot{M}$ = $3x10^{-11}$ M_{sun} yr^{-1} (red graphs) and 10^{-10} M_{sun} yr^{-1} (blue), for (full) opening angles of the conical polar wind. The flattening of the spectrum at high frequencies indicates transition to the optically thin regime (using Reynolds, 1986). The cross indicates the mass loss for the target χ¹ Ori at 6 GHz and 115 μJy, the diamond the mass loss at 15 GHz and 150 μJy.

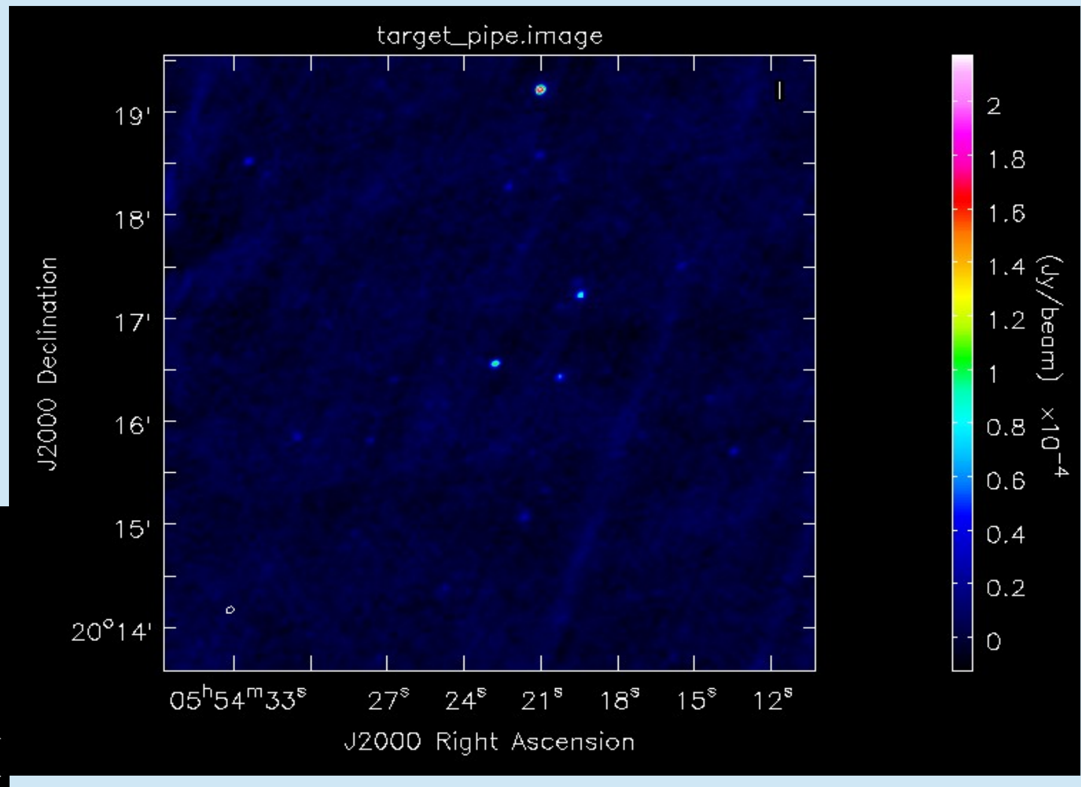
With the JVLA and ALMA telescopes, we will hopefully be able to detect signatures of stellar winds of one of our target stars. These signatures constrain $\dot{M}/v$. With the measurements of Wood et al. (2002; 2005) which constrain an $\dot{M}\,v^2$, the mass loss rate could in principle be determined.

Targets: solar analogs of different ages covering the evolutionally stages of the Sun:

- χ¹ Orionis: very close (8.7 pc) and very active G1V solar analog with an age of ≈ 300 Myr; C and Ku band, from JVLA and ALMA (100 GHz)
- EK Draconis: a G0V, near-ZAMS star at an age of 100 Myr, distance of about 34 pc; C and Ku-band; from JVLA
- future targets: κ¹ Ceti (G5V, age ≈ 650 Myr, d = 9.2 pc), JVLA
  π¹ UMa (G1V, age ≈ 300 Myr, d = 14.3 pc); JVLA

First Results: Image of χ¹ Ori

Fig.3 (right): JVLA image showing a detection of the young solar-like star χ¹ Ori in C band (6 cm) in C configuration after flagging and calibration with an angular resolution of about 3.5 arcsec (source in the center of the image).



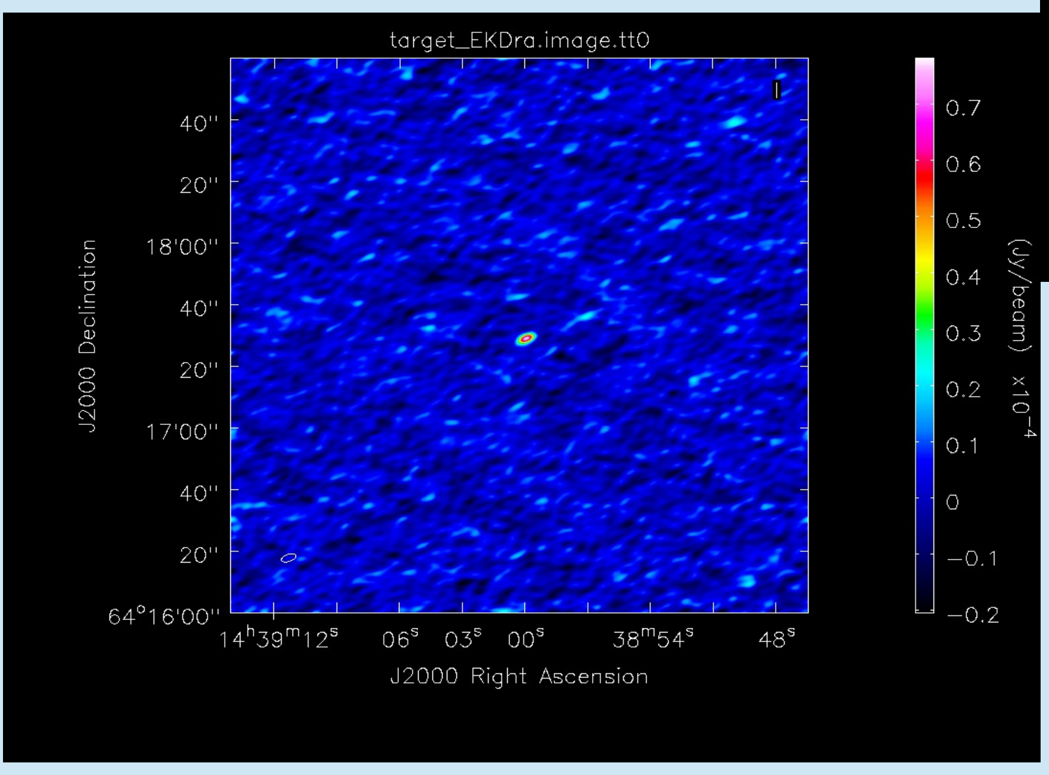


Image of EK Dra

Fig. 4 (left): JVLA image of EK Draconis in Ku band (2 cm) in C configuration with an angular resolution of 1.4 acsec (source in the center).

Results of the χ¹ Ori observation:

- integrated flux I = 114.6 +/-2.5 μJy /beam in C-band
- I ≈ 150 +/- 50 μJy /beam in Ku-band (from several observations)

Judging from Fig. 2, this radio flux corresponds to a mass loss rate of about $\dot{M}=3\times 10^{-11} M_{sun}\,yr^{-1}$ (opening angle of 30 degrees). From spectral information, we suspect, however, that this is predominantly coronal emission. Therefore, I defines an upper limit for the bremsstrahlung of χ¹ Ori for C-band and $\dot{M}$ given above is an upper limit for the wind mass loss rate.

Outlook & future work

- Determine mass loss rates or upper limits for all targets with different ages (see Reynolds, 1986 and Fig.2) and compare them to results determined by Lyman-α absorption of Wood et al., (2005)
- combine JVLA data with upcoming ALMA observations

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