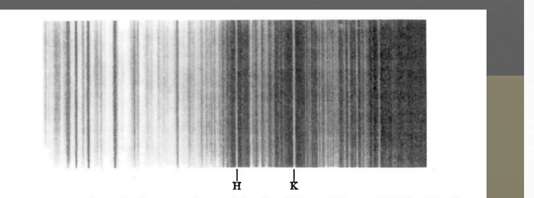
The solar-stellar connection, a historical perspective

Alicia Aarnio, UM Astronomy



Spectrum of σ *Geminorum* taken with the Zeiss triplet and U.V. objective-prism, 1913, March 9. Enlarged and broadened about 12 times.

Two problems arise in this connection. It remains to be shown whether the emission lines of the star have a possible variation in intensity analogous to the sun-spot period. It is known as a result of the investigations of Deslandres[1] and of St. John[2] that the centers of the calcium emission of the sun have a radial outward motion of 1 km per second. A more accurate determination of the wave-lengths of the calcium emission of the stars should prove whether or not a greater total intensity of emission is accompanied by a greater velocity of ascent.

G. Eberhard
K. Schwarzschild

1913

TEN YEARS' WORK OF A MOUNTAIN OBSERVATORY

A brief account of the Mount Wilson Solar Observatory of the Carnegie Institution of Washington

BY

GEORGE ELLERY HALE

WASHINGTON, D. C.
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1915

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appreciable disk. We may safely infer, from many observations of recent years, that thousands of the stars are almost identical in character with the sun, though some are much larger or smaller and some are in earlier or later stages of development. But if we wish to know what a star really is we

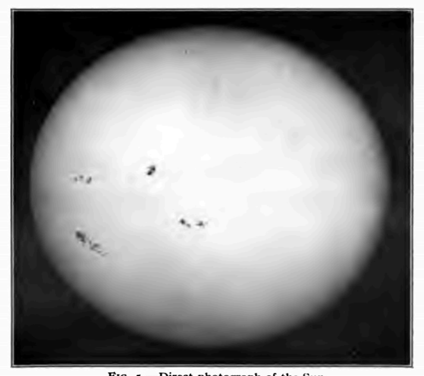

Fig. 5.—Direct photograph of the Sun.

must approach it closely, and this is possible only in the case of the sun. Indeed, because the sun was regarded as so important, offering so many opportunities to increase our knowledge of its nature, the observatory was conceived primarily

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for solar research. But the necessity for seeking, among the stars and nebulæ, for evidence as to the past and future stages of solar and stellar life, rendered a broadening of scope advisable from the outset. Much attention is therefore devoted to the sun as the chief among the stars, but the essential means of attacking the more distant objects of the universe have also been provided.

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STELLAR PROBLEMS.

These examples will suffice to illustrate the character of the solar work in progress on Mount Wilson. Let us now consider for a moment the broader bearing of these results, each of which has a wide range of application. Thousands of stars, in the same stage of evolution as the sun, doubtless exhibit similar phenomena, which are hidden from us by distance. No possible increase in the power of our telescopes, so far as can be judged from present knowledge, will ever render star images comparable in size with the solar image. But the knowledge derived from the study of the sun prepares us to solve problems otherwise much more difficult. For example, the results of the work on sun-spot spectra, in harmony with other phenomena, render it safe to attribute to reduced temperature the bands and the weakened and strengthened lines in the spectra of Arcturus and other stars. This conclusion will assist in arranging the stars on a temperature basis, showing the gradual changes they have passed through in the different periods of their existence. Again, the peculiar behavior of certain lines in the sun has recently led to the detection of an interesting relationship between a star's spectrum and its absolute magnitude, which provides a new and very effective way of determining stellar distances and throws much new light on the evolution problem.

THE SUN AND THE WELFARE OF MAN

CHAPTER I

WHY STUDY THE SUN?

"And Joseph said unto Pharaoh, The dream of Pharaoh is one: God hath shewed Pharaoh what he is about to do."

"Behold, there come seven years of great plenty throughout all the land of Egypt:

"And there shall arise after them seven years of famine; and all the plenty shall be forgotten in the land of Egypt; and the famine shall consume the land."

The sun was God in Egypt. Could the sun do these things?

On a mountain top in Chile, the Smithsonian Institution maintains a queer observatory. It has no telescope! "Impossible," you say, "an observatory without a telescope." Rather than "on a mountain," it would have been more accurate to have said "in a mountain." The delicate observing instruments are contained in a dark tunnel, over 30 feet deep, running horizontally southward from near the summit of the northern face of the peak. The observatory does no work at night, for its studies are confined to a single star, our own star, the sun. This orb is so bright that it needs no telescope to concentrate its rays.

Like Joshua of old, the observers make the sun's rays stand still. There is an instrument called the coelostat

[1]

Abbot, 1929

TABLE 17

Comparison of Emission Lines in T Tauri Stars and Solar Chromosphere

	Chromosphere			T Tau Stars			Chromosphere			T Tau Stars	
Element	No. Lines	Mean Intensity	Mean Height	No. Lines	Mean Max. Intensity	Element	No. Lines	Mean Intensity	Mean Height	No. Lines	Mean Max. Intensity
Ca II	2	200	14,000 km	2	50	Sc II	4	24	2,220 km	4	2
H	6	160	8,900	6	40*	Al I	2	30	2,000	2	2
Sr II	2	70	6,000	2	4	Fe II	7	25	1,700	7	12
Ca I	1	40	5,000	1	5	Ba II	4	29	1,550	0	.....
Mg I	6	46	4,170	6	1	Cr I	3	21	1,500	3	2
He I	11	20	3,840	3	2	Na I	2	22	1,500	2	1
He II	1	2	3,500	1	1	Cr II	1	15	1,500	1	2
Ti II	21	29	2,410	19	2	Fe I	25	13	1,470	21	3

* Mean of four lines (Hα–Hδ) only.

This bright-line spectrum is quite different from other stellar emission spectra, but its resemblance to that of the solar chromosphere is sufficient to invite a detailed comparison.

Joy (1945): T Tauri Stars recognized as distinctly solar-like.

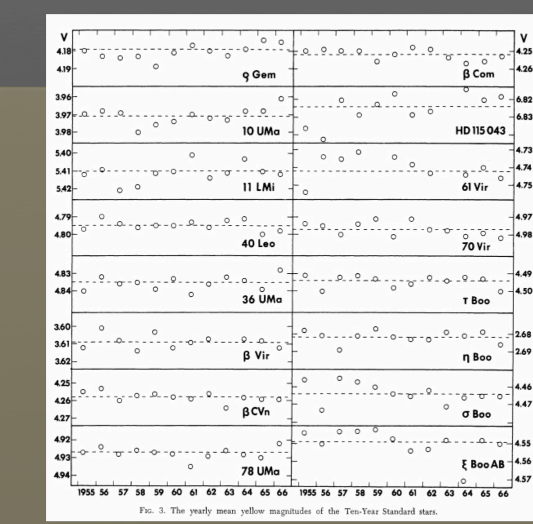
Let us first recall some of the more obvious arguments for the existence of a very high temperature in the corona:

1. The high mean stage of ionization as revealed by the emission lines.
2. The breadth of the emission lines, if due to thermal Doppler effect. The broadening of the lines might also be caused by macroscopic irregular motions (turbulence) or radial motions of the matter.
3. The blurring out of the Fraunhofer lines in the continuous spectrum of the inner corona, assumed to be an effect of the velocities of the scattering electrons.
4. The absence of the Balmer lines in the emission line spectrum of the corona, explained by the electrons being too fast to be captured by the protons.
5. Dynamical considerations showing that great thermal velocities are necessary to balance the gravitational forces in order to explain the observed density gradient of the corona.

All these observations point to temperatures higher than a quarter of a million degrees.

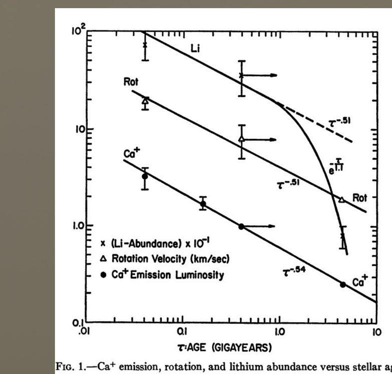
Independently of the identification of the coronal lines, Alfvén * came to the conclusion that the corona might consist altogether of particles with very high energy and derived from the density function a temperature of about one million degrees. On certain assumptions Alfvén finds that the energy necessary to maintain this high temperature of the corona would be about 10^{-5} of the total energy radiated by the Sun, and that the total energy contained in the corona would be produced in about two hours.

Edlén (1945) observed forbidden coronal lines, questioned source of heating



"The present paper is the final report on the search for the solar variability conducted at the Lowell Observatory. No more observations of this kind are planned at this Observatory."
—Jerzykiewicz & Serkowski 1966 Low. Ob. Bull 6 295

Late 60's-early 70's: Orbiting Astronomical Observatories launched, including OAO-3: *Copernicus*, UV telescope



Skumanich, 1972

Zwaan, 1977
Thinking about how fields & spots may be detected on stars, commenting on necessity of looking for them for a robust dynamo theory

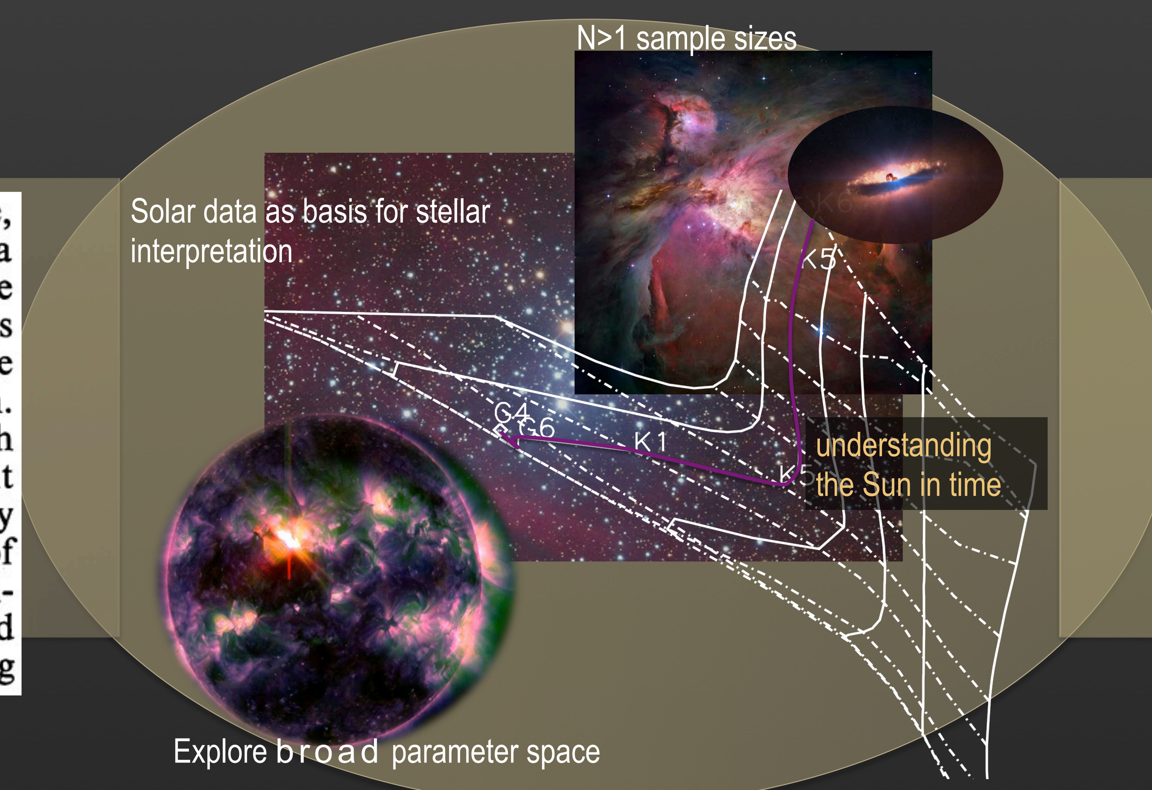
5.4 - *Sun and stars*

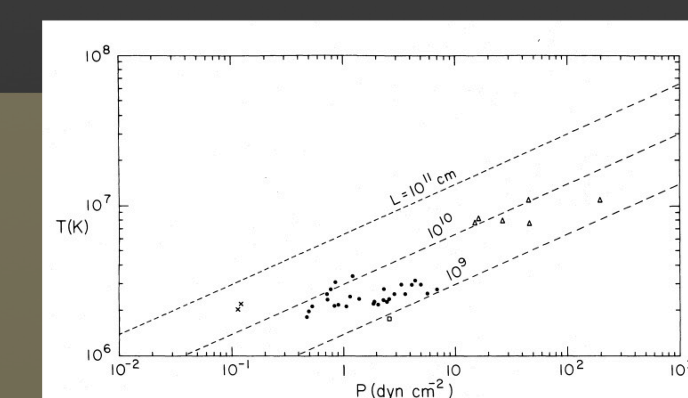
Clearly, the development of a comprehensive theory for differential rotation, dynamo action and magnetic structure should be guided by the *combined* solar plus stellar data. On the other hand, theoretical concepts may inspire acquisition of revealing observational data, particularly from stars. The subject of magnetic structure and rotation is closely related with convection, coronal heating and stellar wind. For a brief discussion of these matters see Kippenhahn (1973).

IUE satellite launched: studies of stellar chromospheres+transition regions take off (Boggess et al. 1978a,b)

Olin Wilson, 1978: Chromospheric Variations in Main-Sequence Stars
Results of first 12 years of Mt Wilson HK Project

Students of the solar cycle have had the advantage, at least in modern times, of the ability to study how a number of observable solar phenomena vary in the course of a cycle. But they have also had one serious disadvantage: all this information applies to a single star of given mass, age, and chemical composition. This survey has demonstrated that other stars, with different parameters, have analogous cycles, and it has given at least a rough idea of how the frequency of cyclical behavior varies along the relevant part of the main sequence. To be sure, the information content is rather small—only periods, amplitudes, and curve shapes. Even these are vastly better than nothing.





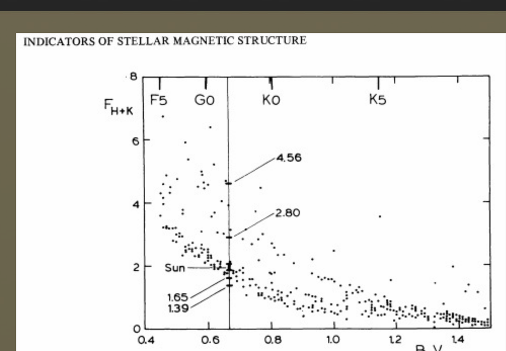
Rosner, Tucker & Vaiana (1978)
RTV coronal loop models related pressure, heating, loop properties, were adopted by stellar community

Hardorp, 1978: *The Sun Among the Stars. 1. A Search for Solar Spectral Analogs*

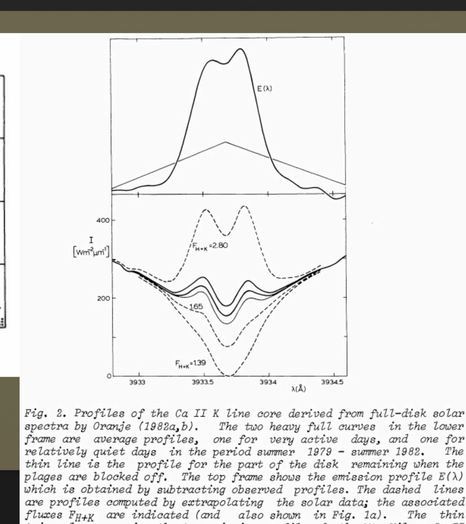
- Hardorp (1978): HD 44594 "indistinguishable from solar"
- Dorren & Guinan (1994): β Hyi= "solar proxy"
- Gray (1995): using line ratios+large sample, only found 6 with Teff +/-20K solar T_{eff}
- De Strobel (1996): of 105 stars owith solar-like colors, only 5 agree in Teff, Mbol, [Fe/H]. Best? 51 Peg, HD 76151
- Henry et. Al (1997): Nstars project- where are the Suns?
- Hall (1997): solar analogs meeting, 18 Sco may be nearest solar twin
- Difficulty finding solar twins, K. G. Strassmier (2004) argues, could mean stars with solar parameters are rare. Or, maybe we haven't looked deep enough yet!
- Bazot et al. (2012): Interferometry and asteroseismology for solar twin **18 Sco: $1.010\pm0.009\ R_\odot$, $1.01\pm0.03 M_\odot$**

Holt, 1979: stellar coronae as 2-temperature plasmas

"With the results of solar physics in hand, we can cautiously begin to study the analogous stellar physics."
Baliunas 1983



Zwaan (1983): Solar Ca H and K observations, full disk and with plage excluded.



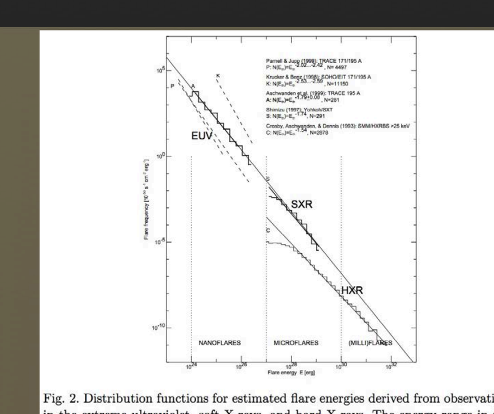
Dupree et al. (1993): stellar atmospheres show smooth temperature gradients, peaking ~10x hotter than Solar

Noyes et al. 1984
R' activity parameter defined

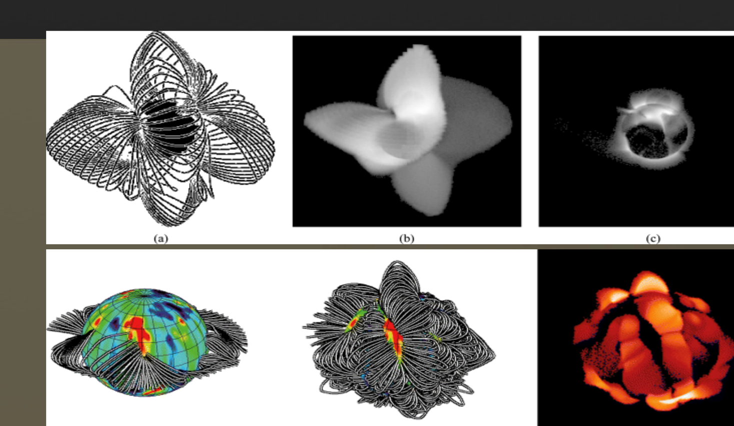
Phillips et al. 1995: ULYSSES data show fast solar wind originates low in corona

By 1998, two-temperature coronal model disfavored. Objects found with atmospheres intermediate to solar-type and alpha-Ori type (Schröder et al. 1998).

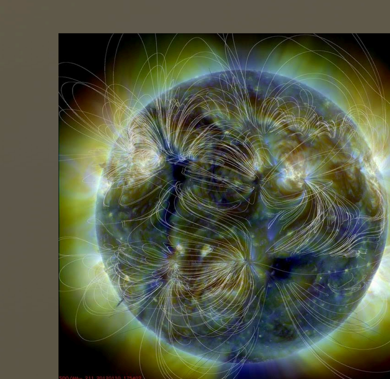
Strassmeier & Rice, 1998
High latitude and polar stellar spots, who ordered that?

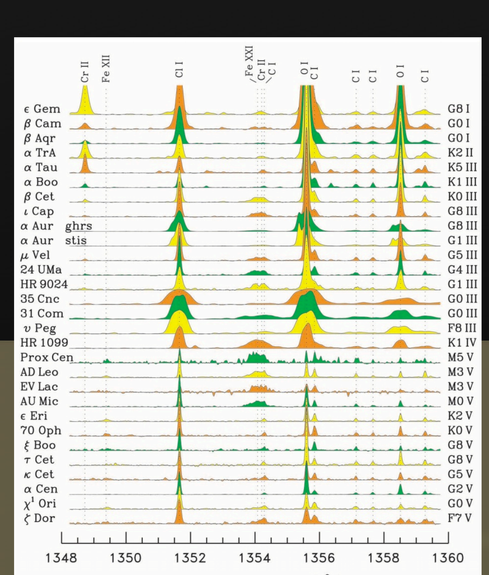


Aschwanden, 2001: RTV models insufficient to describe coronal loops

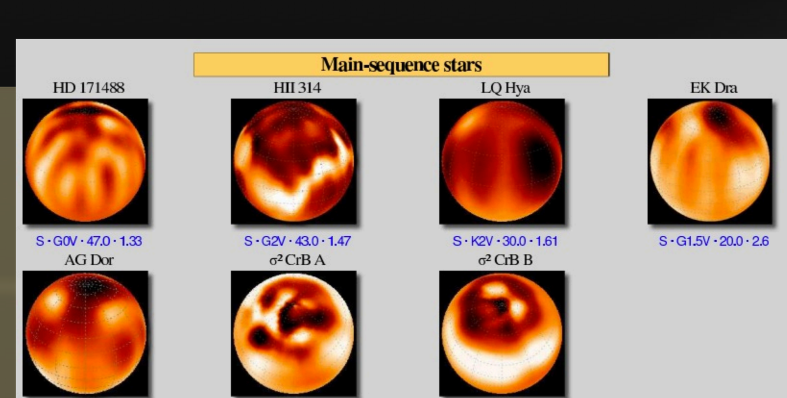


Jardine 2002, 2006: Zeeman-Doppler imaging+PFSS extrapolation. X-ray measurements reproduced by models.



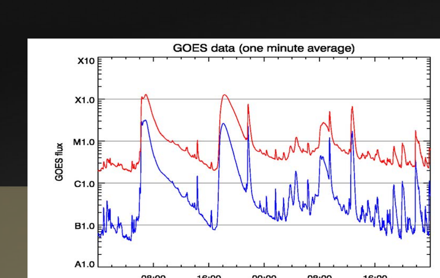


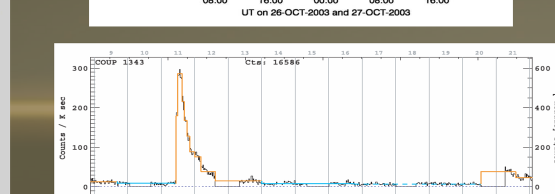
Ayres et al. (2003) STIS observations of forbidden lines. Solar Maximum Mission, Apollo Telescope Mount on *Skylab*, and SUMER on SOHO also found more forbidden lines than Edlén's original Fe X and XIV.



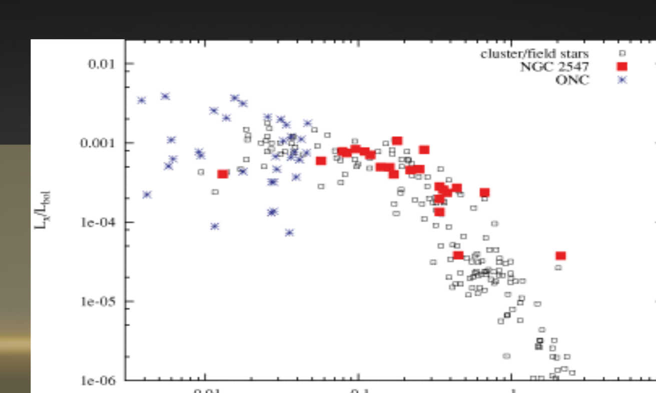
Strassmeier, 2004: Connection, and disconnection? Disconnects:

- Where are the solar twins?
- Dynamo-activity relationships may suggest multiple dynamo possibilities



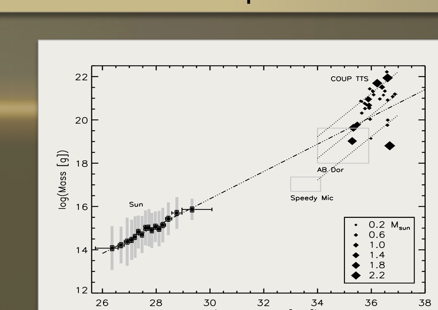


Getman et al. (2005): *Chandra* Orion Ultradeep Project reveals energetic flares, Favata et al. (2005) model loop sizes based on formulation of Reale et al. (1998): ~10's of stellar radii!!

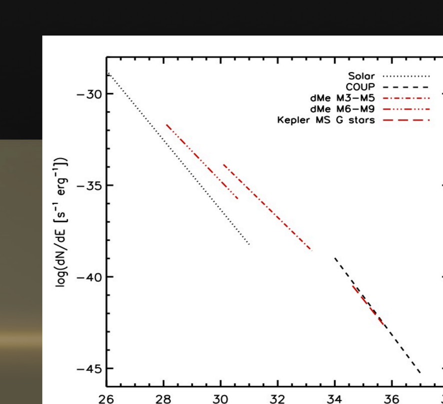


Jeffries et al. (2006) Rotation-activity studies indicate 'saturation' phenomenon. Why? Coronal stripping (James et al. 2000)? Poleward migration of active regions reducing coronal filling factor (Stepien et al. 2003)?

Nandy & Martens (2007) make important distinction: solar and stellar flare studies→space weather; long-term, N>>1 stellar variability studies→space climate

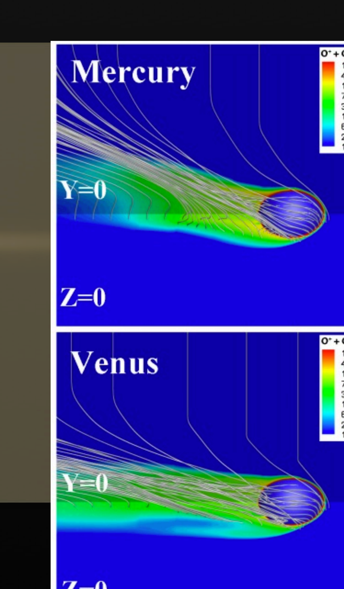


Aarnio et al. 2010, 2011, 2013 make first stellar CME mass loss estimates for T Tauri stars



Solar and stellar flares follow cumulative frequency distribution N(E) dE = $E^{-\alpha}$ dE with α ~1.7 to 2. *Kepler* finds "superflaring" G stars (Maehara et al. 2013); dMe flaring rates quantified (Hilton, 2011).

Future: solar-stellar connection → solar system-stellar connection



Cohen et al. (2015) model stellar wind-planetary magnetosphere interaction for Mercury and Venus analogs orbiting an M dwarf.