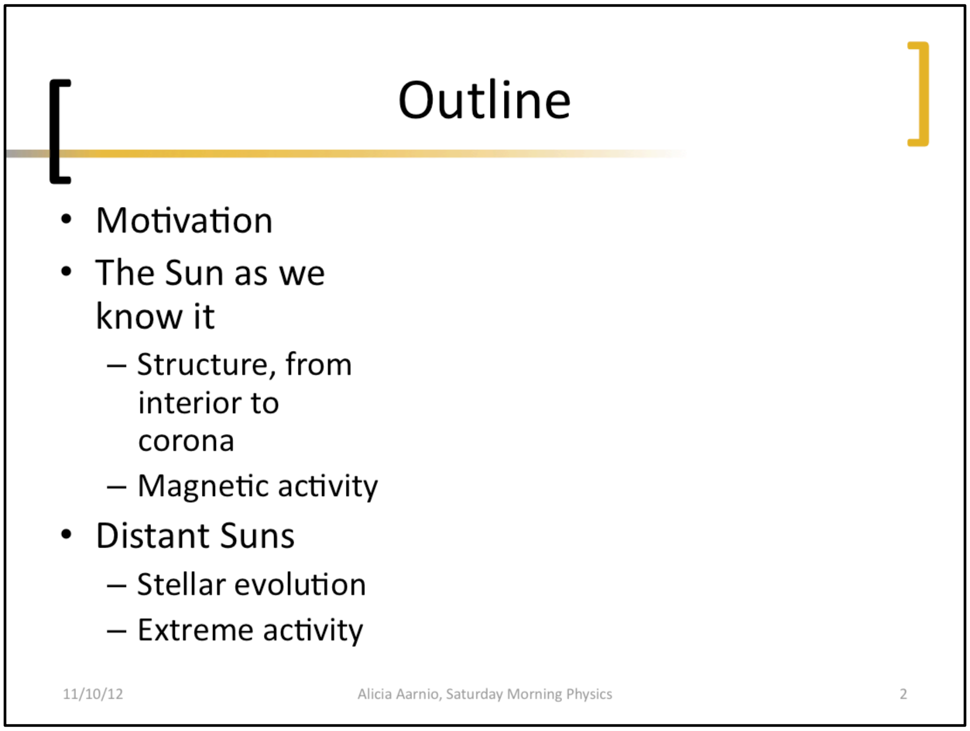
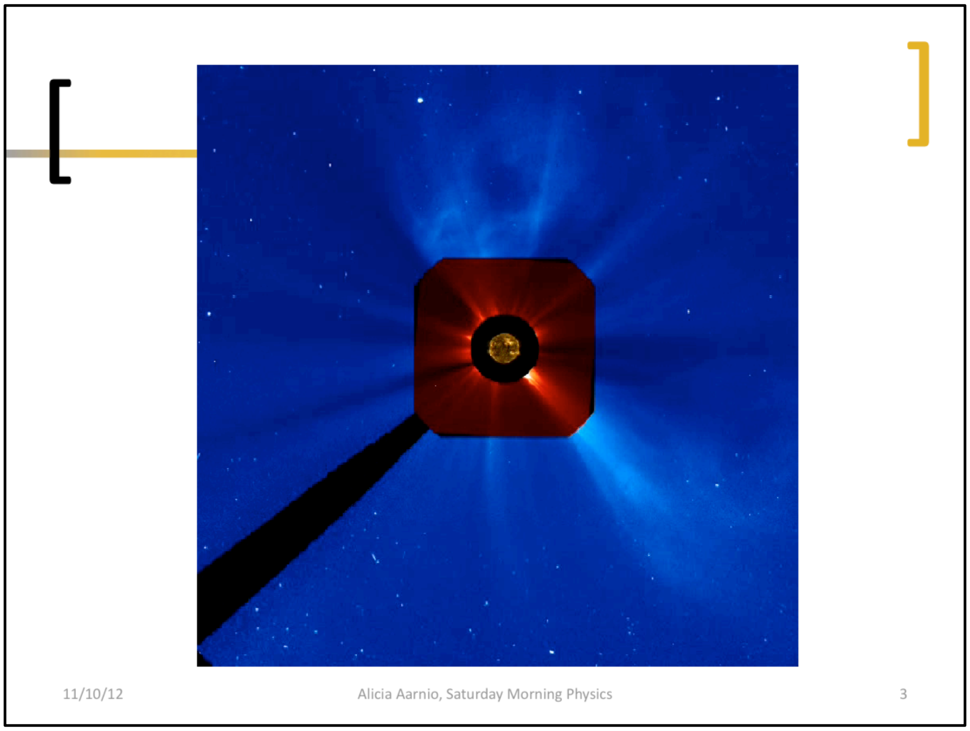
Our closest star provides astronomers with a unique opportunity to observe, in high spatial and temporal resolution, the spectacular interaction of hot plasma and magnetic fields which occurs on a daily basis. While we cannot observe these same phenomena in such detail on distant stars, what we do see in solar-type stars at a variety of ages helps us to piece together the history of our Sun and unravel how our solar system came to be. In a mutually beneficial way, solar physics and astrophysics research complement each other well, studies of each serving to fill gaps in our understanding of the other. In this lecture, I will discuss our view of the Sun in time: today's Sun helps us interpret what we observe in stars, and young, solar-type stars give us a glimpse of the solar system in its youth, in the epoch of planet formation.



We care about the Sun for the immediate threat that space weather can pose to our technologically driven way of life. We care about young Suns for philosophical and intellectual reasons: how did our Sun and solar system come to be?

Today, we're going to start deep within the Sun's core, work our way out to the surface and then corona, and then we'll go millions of miles away to young Suns- snapshots of what the Sun was like in its youth.

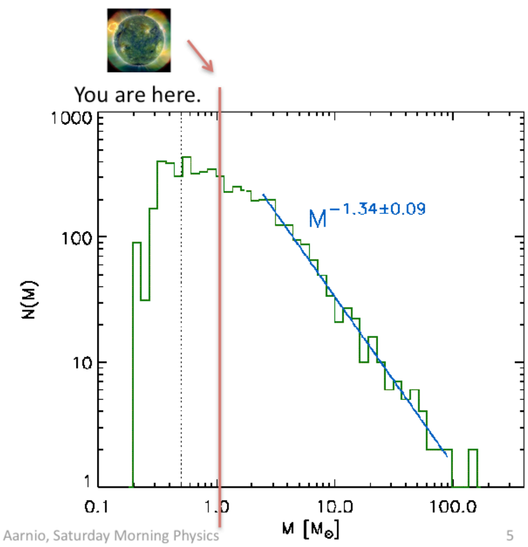


Source: NASA SDO (Solar Dynamics Observatory) youtube channel http://youtu.be/GzdVxHkfd_k

- Motivation
- The Sun as we know it
  - Structure, from interior to corona
  - Magnetic activity
- Distant Suns
  - Stellar evolution
  - Extreme activity

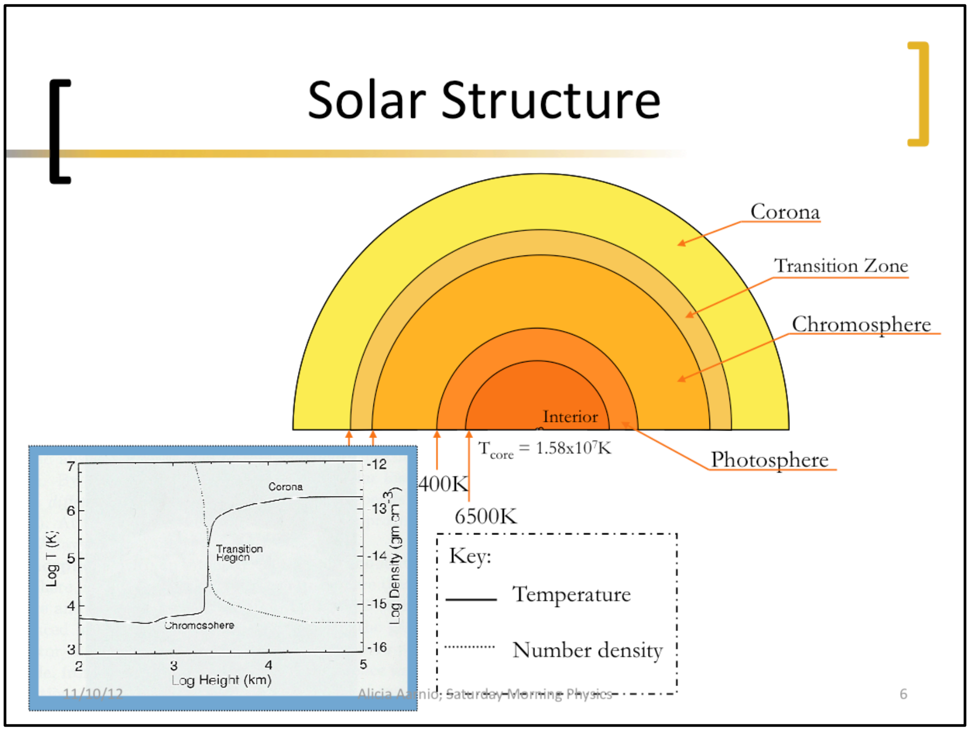
Solar Spec Sheet

- $M_\odot = 1.99e^{30}$ kg
- $R_\odot = 6.96e^{8}$ m
- $L_\odot = 3.83e^{26}$ W
- $T_{eff} = 5780$ K



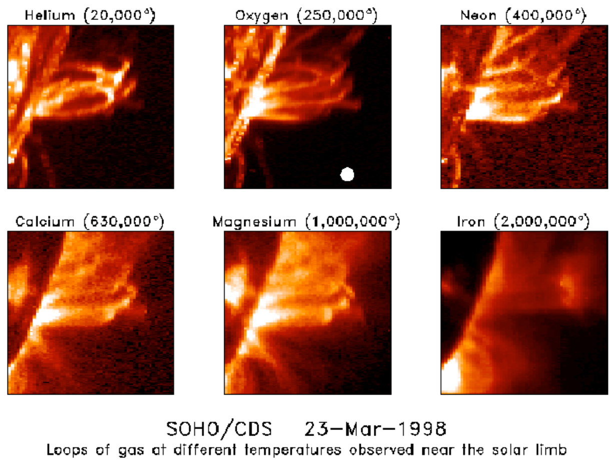
Sir Isaac Newton was the first to estimate the mass of the Sun by using the parallax to derive a mass ratio of the Sun to the Earth. The Sun = 332946 Earth masses.
Where does the Sun fit, property-wise, into the grand scheme of things? Turns out, it's pretty average.

http://www.astro.rug.nl/~etolstoy/ACTUEELONDERZOEK/JAAR2005/rob/salpeter%20imf.bmp

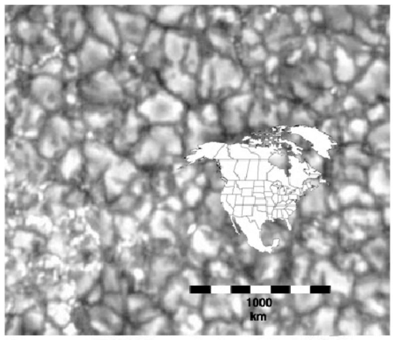


General picture of the solar interior and atmosphere. The corona is a hot, low-density plasma; the species you can see tell you about the temperature. How do we know these values? The ratios of species observed in UV and X-ray spectra.

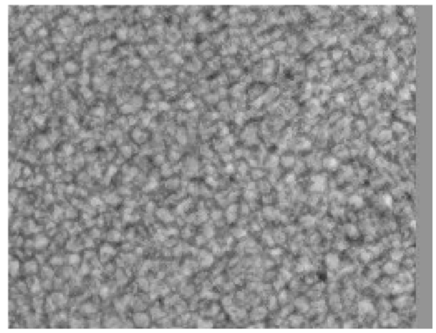
Solar Structure



Granules



Photospheric granulation, G. Scharmer
Swedish Vacuum Solar Telescope
10 July 1997



60 minutes of granulation, near infrared

Granulation is due to convective cells in the photosphere; structure tends to dissipate in about 20 minutes. What we see are the tops of the convective cells.

BBSO (Big Bear Solar Observatory) solar granulation movie. Source: http://www.bbso.njit.edu/Images/movie09.mpg

Putting the M into MHD

- Magnetohydrodynamics (MHD)
- Hydrodynamics, + Lorentz force
  - $F = q\,(E + v \times B)$
- What's special about it? Directional dependence.

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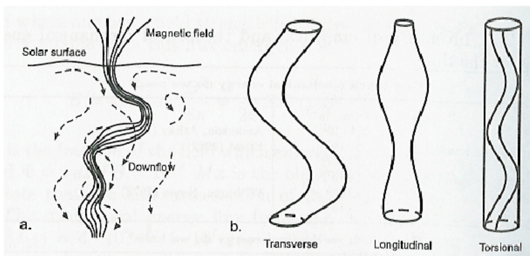
Before we continue, I want to point out that when talking about the Sun and stars, we're talking about plasmas- they behave like charged liquids, which means you see things like convection, but also this material interacting with the magnetic field (and vice versa!)

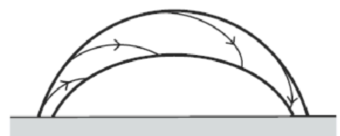
The magnetic field interferes with convection. When the magnetic pressure is lower than the gas pressure, the field gets twisted and pushed around by the plasma. When the magnetic pressure is greater than the gas pressure, you observe the field inhibiting plasma motion (i.e., a sunspot).

Magnetic Flux Tubes

- Magnetic field generated by dynamo in the solar interior
- Bundles of magnetic field lines, called flux tubes, rise to surface

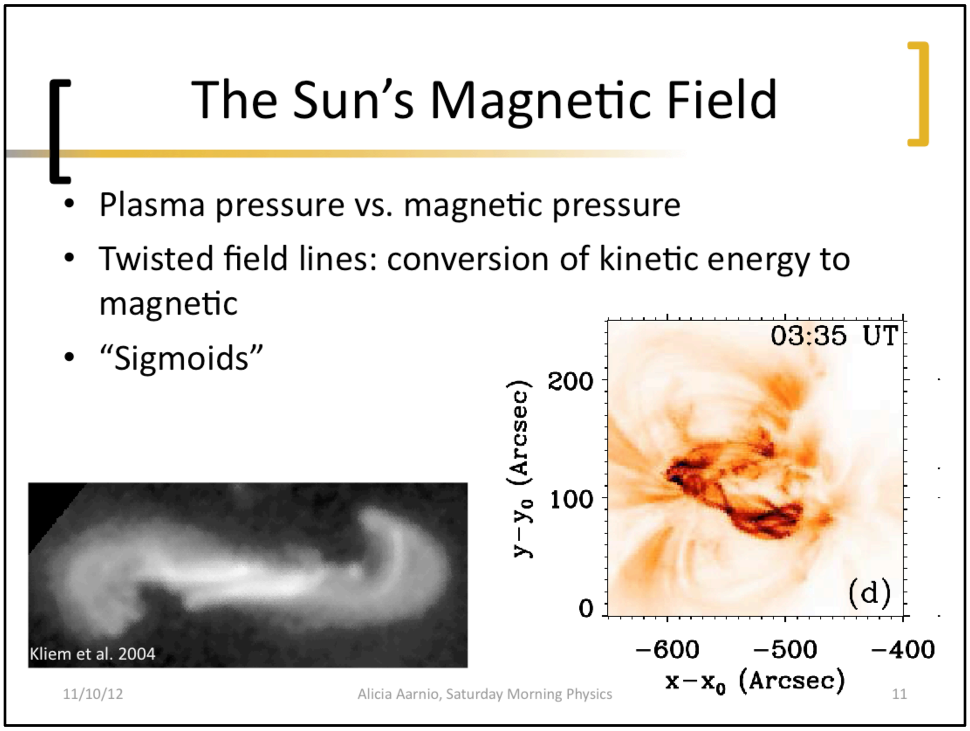


Tayler, 1997



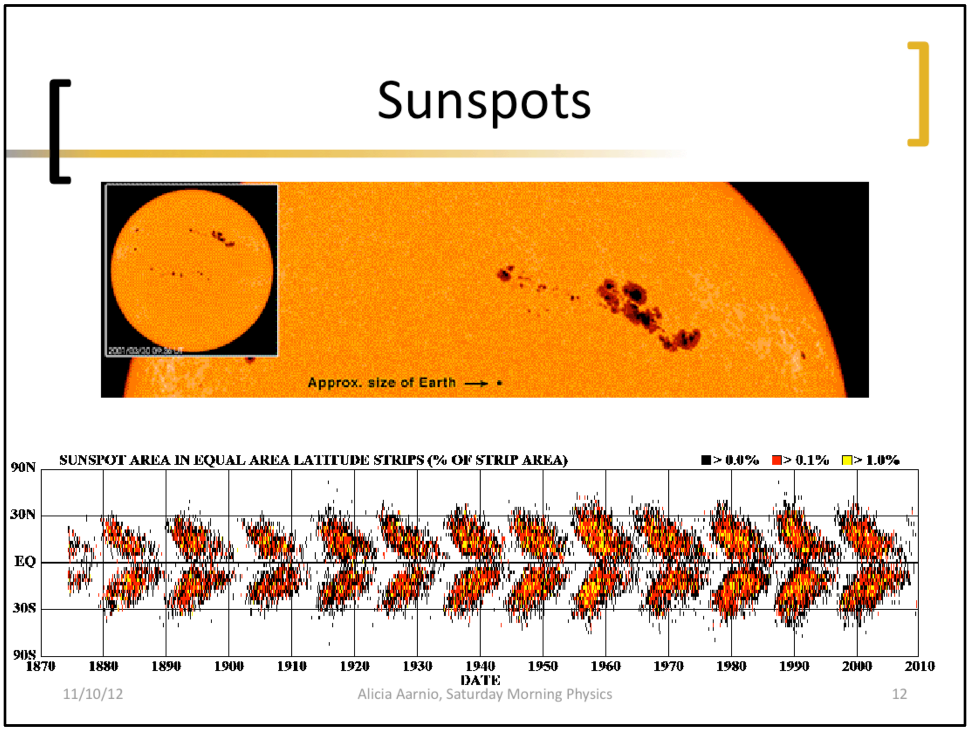
Priest & Forbes, 2002

Magnetic field is generated within the Sun by a dynamo, and as it buoyantly floats up to the surface, it is subject to all kinds of stresses. The flux tubes themselves are coherent, organized structures- they have plasma inside and thus a buoyancy (internal vs external plasma pressure: negative buoyancy and it floats, positive and it sinks). Magnetic tension pulls loops down, magnetic pressure of magnetic field external to the loop lifts it up.



The magnetic field lines are buffeted by the convective cells on their way up-convection is going on, but so is differential rotation; the flux tubes twist and emerge at the photosphere in strange shapes.. What is fundamentally happening is the transfer of energy from kinetic energy, the motion of the plasma, to magnetic energy. With energy stored in the field lines, it's only a matter of time before the system self-arranges into a lower energy state: flares.

Sigmoids are what happens when the magnetic pressure is less than the gas pressure- the gas twists and tangles up the field lines. When the magnetic pressure is greater than the gas pressure, you get sunspots.



<u>Sunspots</u> are cooler regions on the photosphere caused by magnetic activity which inhibits convection. They range from ~4,000-4,500K.

Sunspots are probably the most familiar kind of emerging flux- a huge overdensity of magnetic field will suppress convection, leading to cooler, darker-appearing spots.

Sunspots, an historical note

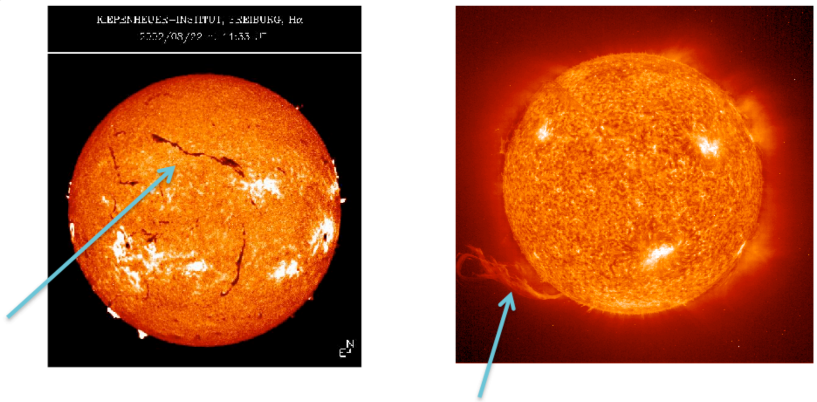
- Observed as early as 800 BC
- Chinese observers saw spots when Sun low on horizon, or if foggy **(please, *do not* try this at home!!)**

-42 MAY 5 / JUN 3 (YUNG-KUANG/1/4/-) CHINA
"The Sun was whitish blue in color and cast no shadows. Right at its center, there were frequently shadows and no brilliance. That summer was cold until the 9th month, when the Sun regained its brilliance."

20 MAR 17 (XIN/WANG MANG/ DIHUANG/1/2/9) CHINA
"The Sun's middle was black, and King Mang disliked it and issued an edict as follows: 'Regarding the darkness recently visible in the Sun, Yin is forcing Yang, and a black vapor is an abnormality.' All the people were alarmed by the strange omen."

ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SUNSPOT_NUMBERS/ANCIENT_DATA/Early_Reports

Filaments and Prominences



Same structure, different viewing angles!

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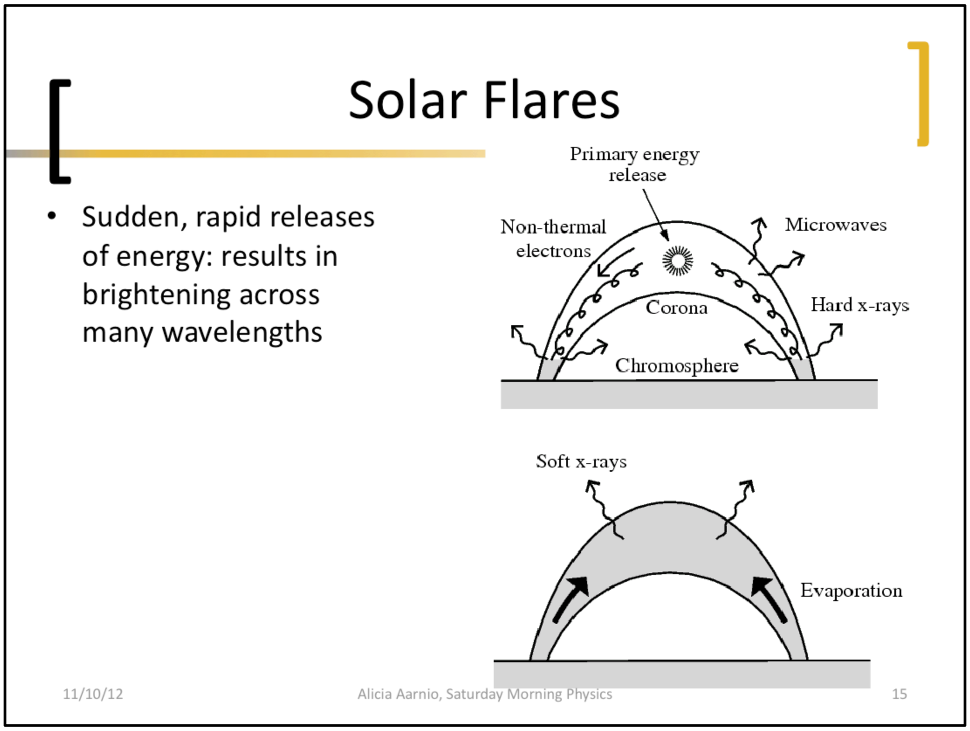
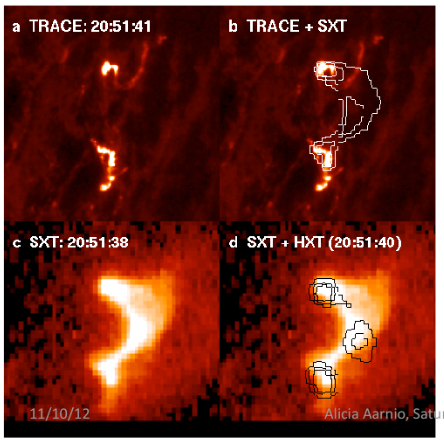
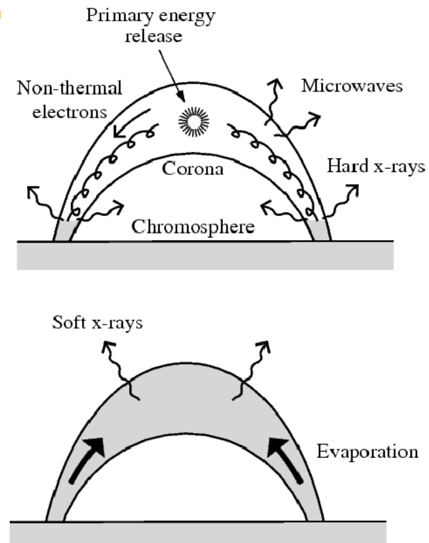
III. Flux tubes rise buoyantly, then erupt!
Cooler, denser gas… eruptive and quasistatic flavors. Eruptive filaments last of order minutes, quasistatic prominences can last a rotation period (~27 days)
Filament eruptions seen to precede what we observe as 'flares', also seen at the core of CMEs



IV. What we see when flux tubes twist, and then release a bunch of energy: flares and CMEs!
Loop cartoon from Priest & Forbes (2002)

Solar Flares

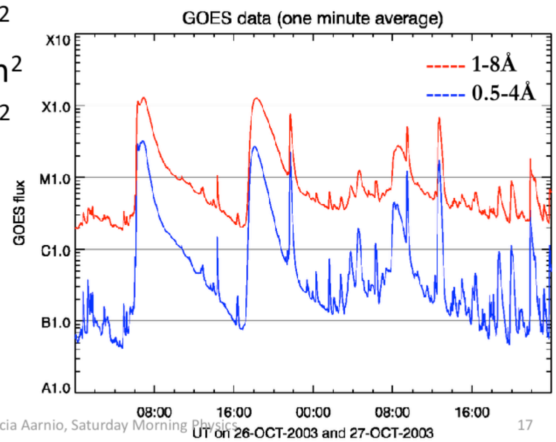


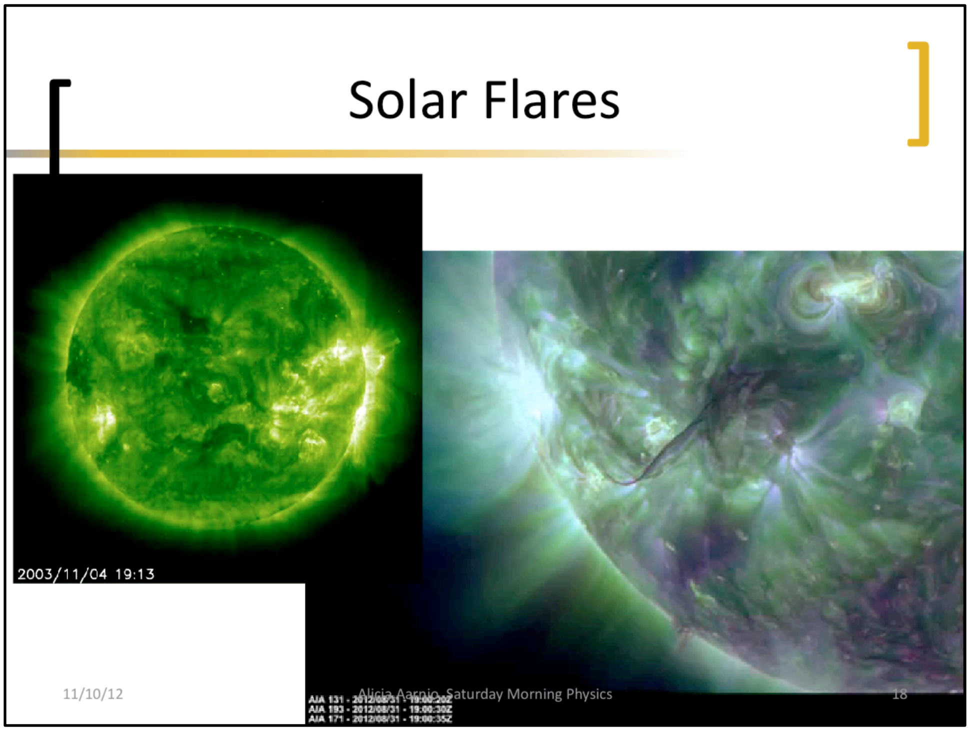


Left: image source http://solar.physics.montana.edu/nuggets/2001/011019/011019.html

Solar Flares

- Classified according to flux received by GOES (Geostationary Operational Environmental Satellite)
- XN → N*e-4 W/m^2
- MN → N*e-5 W/m^2
- CN → N*e-6 W/m^2
- BN < N*e-6 W/m^2





Left: NASA SOHO (SOlar and Heliospheric Observatory) UV movie of an X-class flare. Source: http://sohowww.nascom.nasa.gov/gallery/Movies/flares.html

Right: NASA SDO video of filament eruption + C class flare. Source: NASA SDO youtube channel, http://youtu.be/A8mdEpaXRu0

Coronal Mass Ejections

- Material ejected from the solar corona: enough sometimes to dim the Sun!

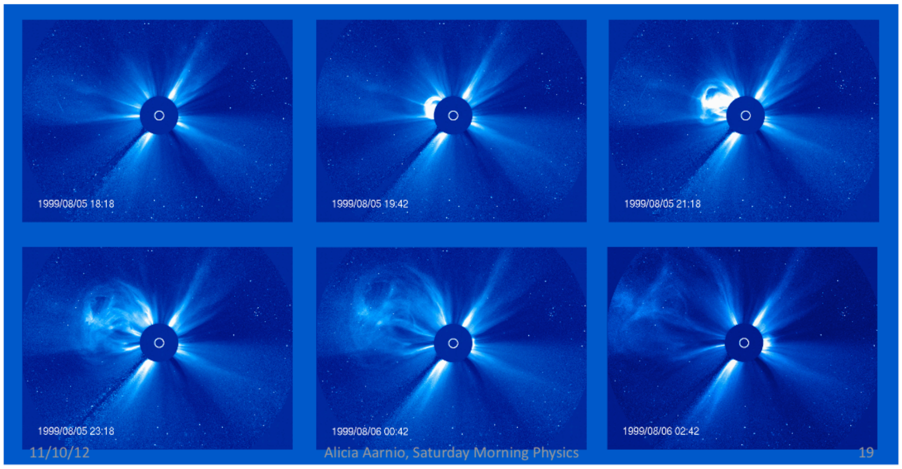
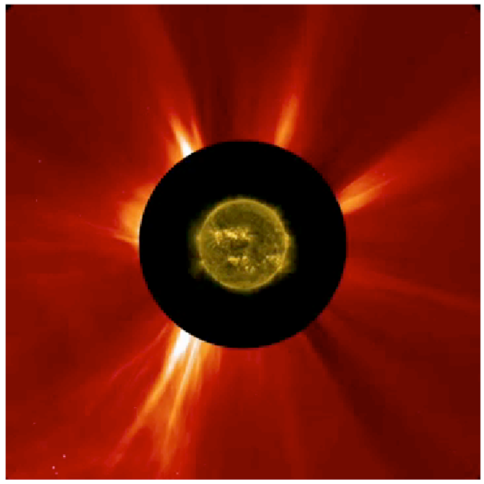


Figure shows CME progression in time; image from LASCO on SOHO

Flares and Solar Storms



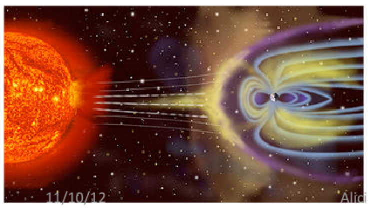
Credit: NASA/SDO, NASA/SoHO

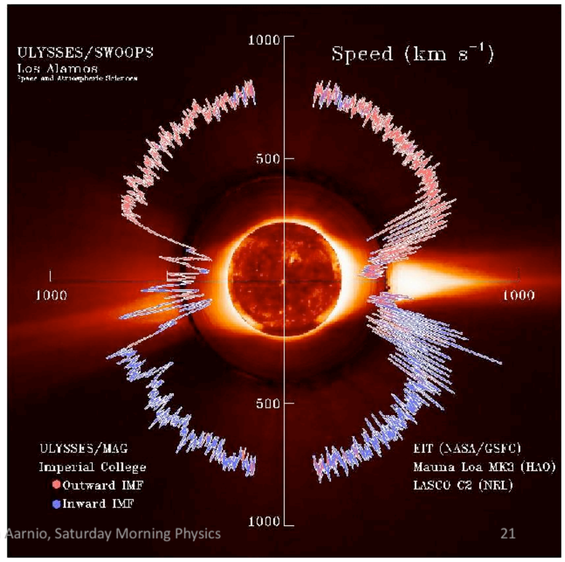
Source = NASA SDO youtube page: http://youtu.be/NqqBuDaEYZA

Often, flares and CMEs are observed together. They're both produces of large scale release of magnetic energy, so it makes sense you'd see them happen together.
The Sun erupted with numerous M-class (medium) flares over a four-day period (July 2-6, 2012), sending substantial, bulbous clouds of particles into space. In this combination of the Sun, seen in extreme UV light by SDO, and its corona, observed by SOHO's C2 coronagraph, we can watch both the activity near the surface and the resultant clouds as they are propelled into space. The powerful Active Region 1515 has been the major producer of these storms and it is likely not done yet.

Solar Wind

- $10^{-14}\ M_{\odot}/yr$





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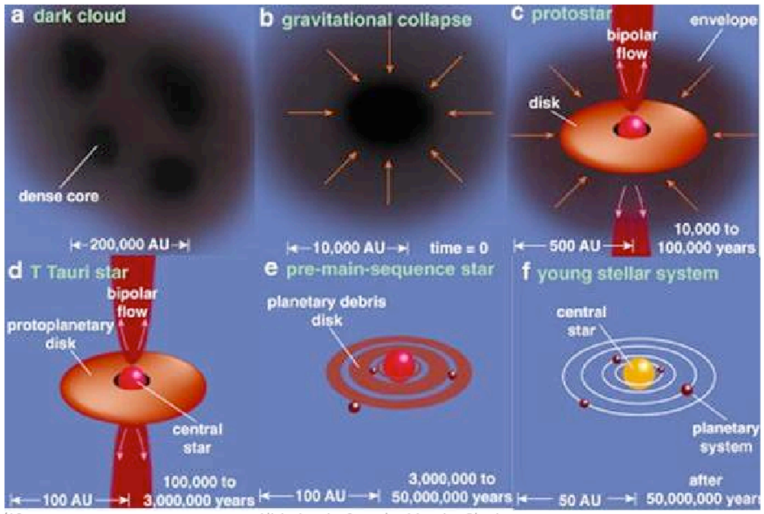
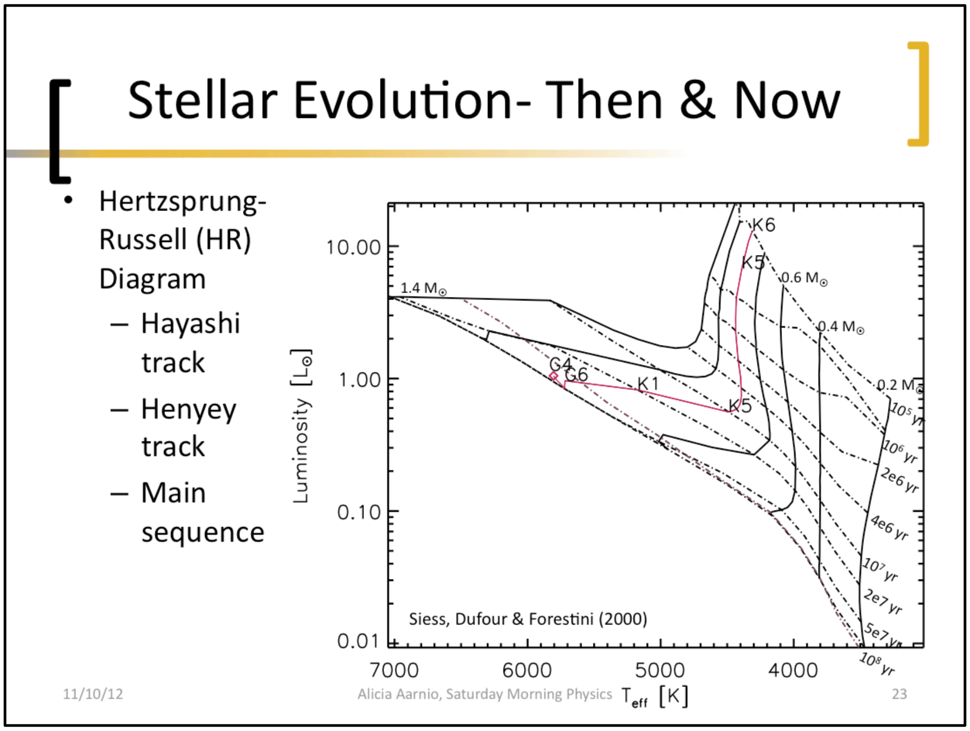
Ulysses image source: http://science.nasa.gov/science-news/science-at-nasa/2008/14jan_northpole/

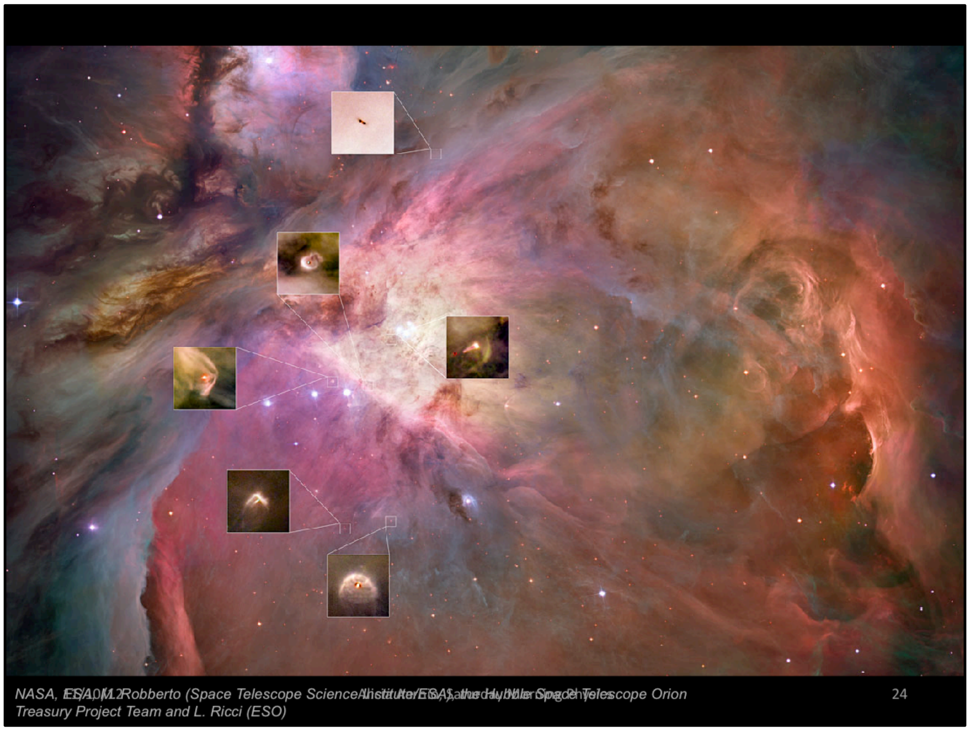
Rewind!



This is a canonical picture of how star formation proceeds.. Let's rewind, look back to the Sun when it was young- we can do this by looking at young, solar-type stars. Graphic from Greene; found at this url http://www.astro.washington.edu/courses/astro421/star_formation_in-class_study.html



Isochrones are 1e5, 5e5,1e6,2e6,4e6,1e7,2e7,5e7,zams,1e8
Masses are 0.2,0.4,0.6,0.8,1.0,1.2,1.4

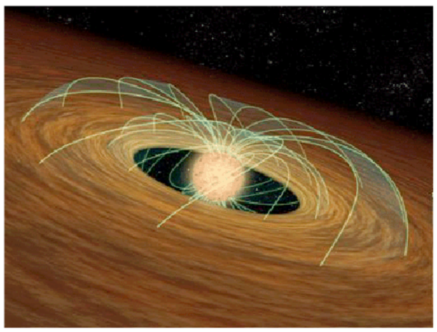

NASA, ESA, M. Robberto (Space Telescope Science Institute/ESA), the Hubble Space Telescope Orion Treasury Project Team and L. Ricci (ESO)
24

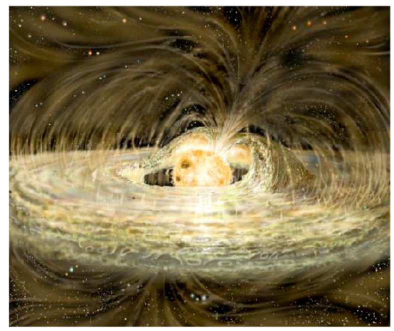
Proplyds..

Going back to 'then'… what effects does having a disk have on young Suns?
Image credit: ONC proplyds: http://www.spacetelescope.org/news/heic0917/

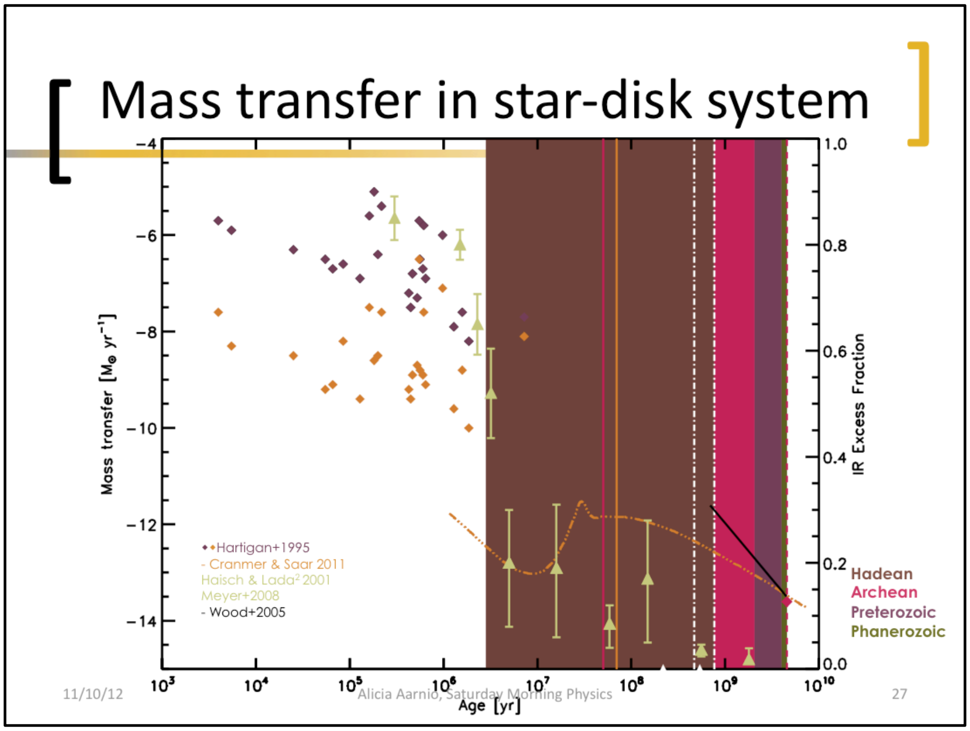
Star-Disk Interaction

- Solar magnetic field: ~1G
- Young Suns: ~1,000G !





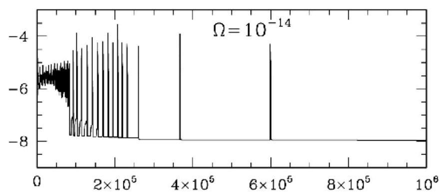
Artist renderings

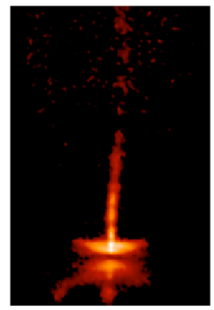


On the plot, I show more steady-state sorts of values, then the animations that pop up afterward talk about some episodic things- FU Ori events with pulses of high accretion, and then a movie of HH 30, which is losing mass from the jet at. On the early end of the plot, the winds and outflows are likely accretion driven, so the energy brought into the system via accretion doesn't change fundamental stellar parameters, it goes right back out in other forms.

Filled areas: geological epochs. Hadean, Archean, Preterozoic, Phanerozoic. Arrows pointing up from X axis are dates of oldest mineral/rock found on Earth- Zircon from Australia, and the Acasta Gneiss.
LHB (late heavy bombardment) marked off with white vertical lines; pink vertical line is when the Sun hit the ZAMS (zero-age main sequence; 5e7 yr); orange vertical line is the moon forming event.
Diamonds are Hartigan, Edwards & Ghandour (1995)- accretion rates measured from veiling, outflow rates from the high velocity component of the [O I] line. Dupree+2005 use O VII for TW Hydra and get Mdot=2.3e-11 Msun/yr, then also use C III and get Mdot=1.3e-12 msun/yr. Using Halpha for TW Hydra, you get 10^-10 msun/yr! Much scatter yet, likely due to our not really knowing exactly where, spatially, the emission is originating
FEPs 24 micron excess data Carpenter+2008 [ref http://adsabs.harvard.edu/abs/2008ApJS..179..423C]
JHKL excess data from Haisch, Lada, and Lada (2001)
Mass loss measurements via astrosphere emission- t^-2.33 power law of Wood+2005 [ref http://adsabs.harvard.edu/abs/2005ApJ...628L.143W]

Mass transfer in star-disk system





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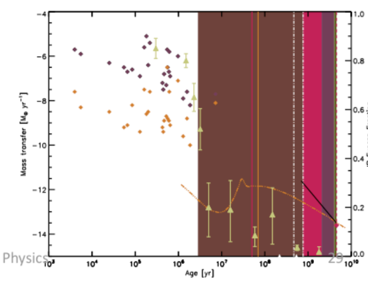
Left: Episodic FU Orionis accretion events , Zhu et al. (2010)
Right: HH30 jet, animated graphic, from http://hubblesite.org/newscenter/archive/releases/2000/32/image/c/

Mass Transfer in Star-Disk System

- Take-away points: mass accreted, mass lost, disk fraction decreases with time
- Initial phases of evolution are rapid
- By comparison, present-day solar wind is weak



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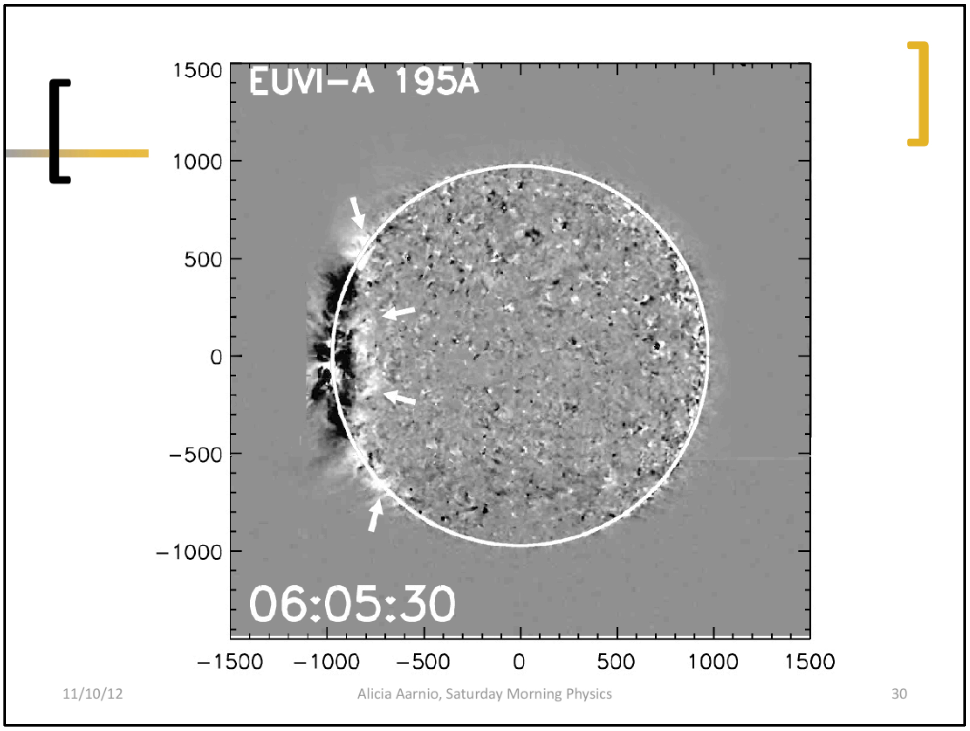
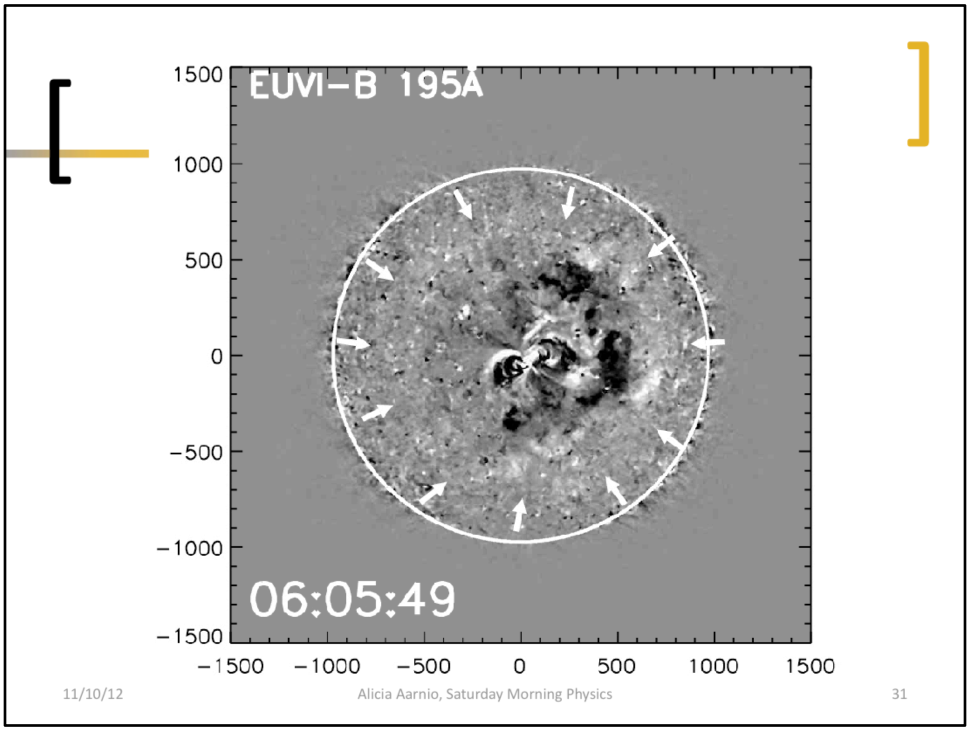
..so what drives the young Sun's wind?

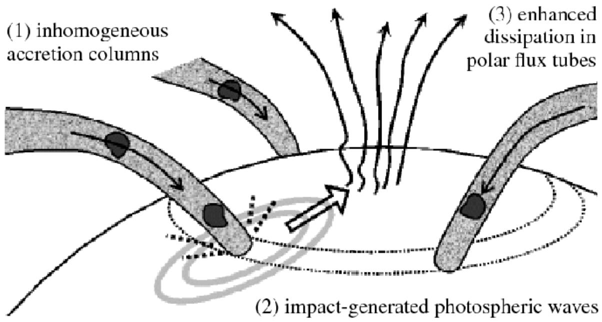


This and following figure I animated from images published by Kienreich, Temmer & Veronig (2009)
Why is the stellar wind so much stronger? A current theory is that material impacting the stellar surface is creating waves which drive material up into open field lines to be carried away!



Observed face-on to propagation, found wave to be slightly brighter in western hemisphere

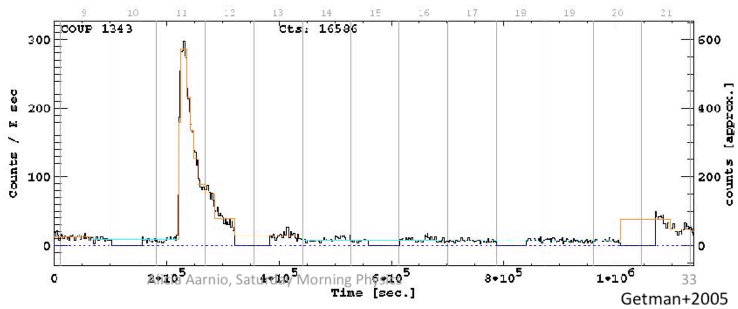
- Accretion-driven stellar winds



Matt & Pudritz (2005); illustration from Cranmer (2009)

Solar-stellar connection: flares

- Magnetic activity
  - Flares much like the Sun, but more frequent, energetic

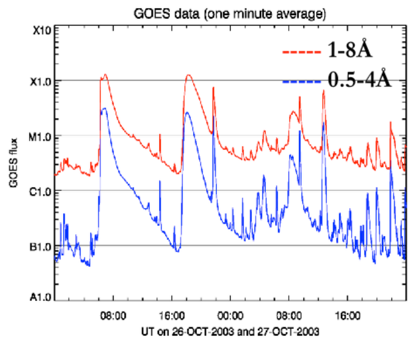


Getman+2005

It's important to understand the magnetic fields of TTS because they transfer huge amounts of energy and provide a conduit for the bulk motion of plasma in the system

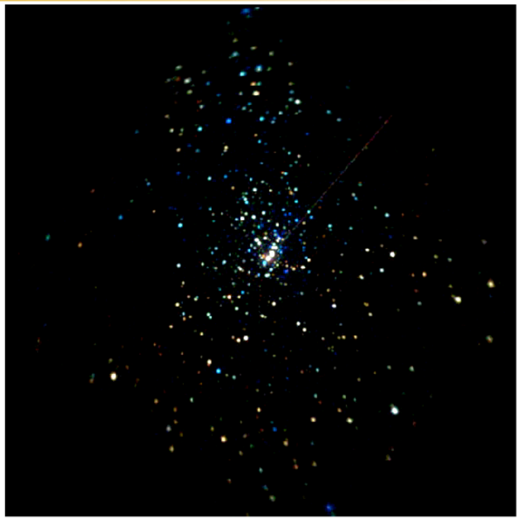
Solar-stellar connection: flares

- Magnetic activity
  - Flares much like the Sun, but more frequent, energetic

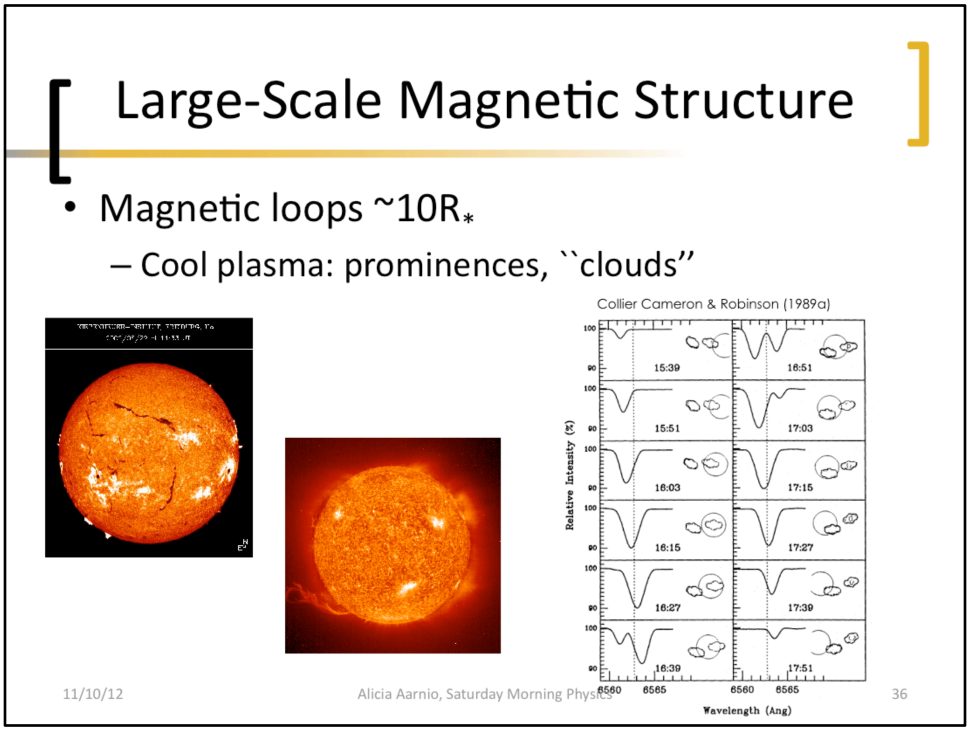


Classifying TTS flares like solar, COUP flares = X300-X40,000!

Solar-stellar connection: flares



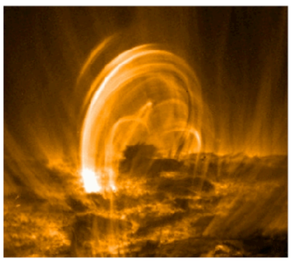
E. Flaccomio for COUP collaboration



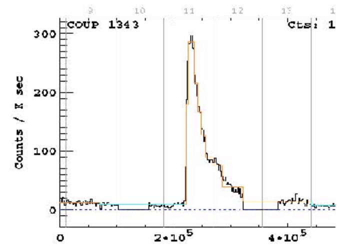
(A. Collier Cameron, AB Dor)

Large-Scale Magnetic Structure

- Magnetic loops ~$10R_*$
  - Cool plasma: prominences, ``clouds''
  - Confining hot plasma: post-reconnection loops

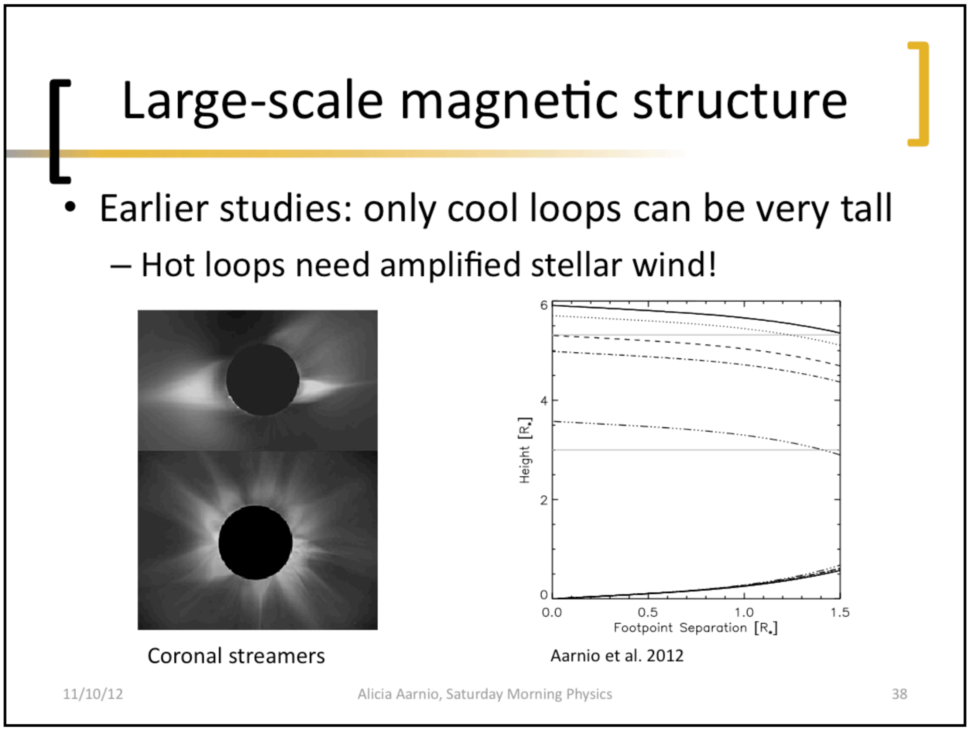


TRACE loop, EUV



X-ray flare decay related to loop size: radiative, conductive cooling

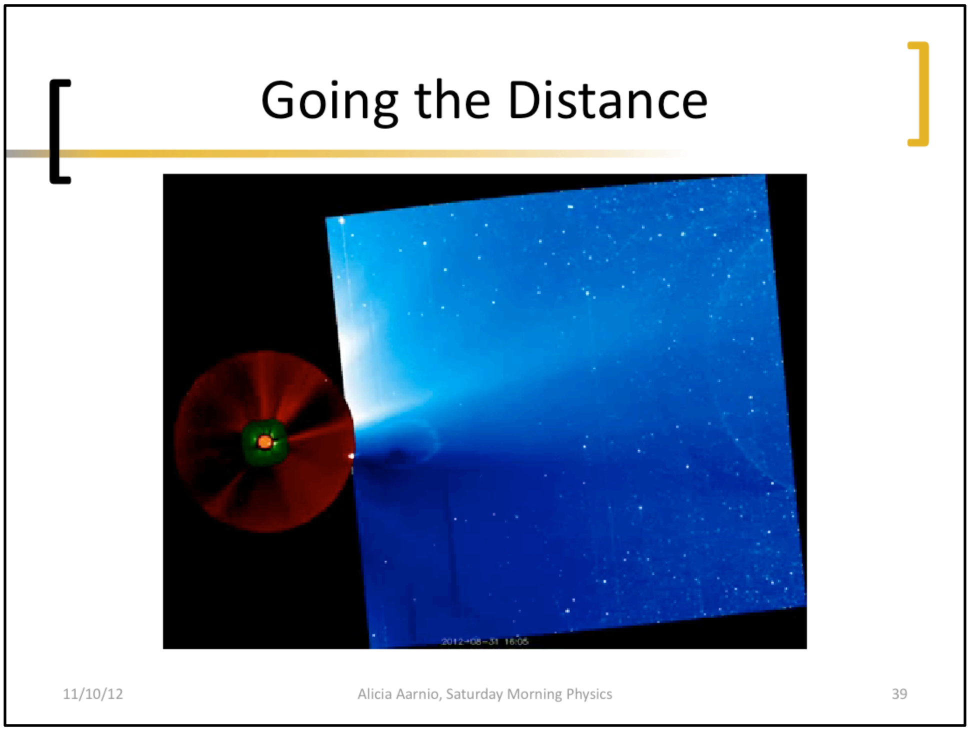
(UCL model, Reale+1997; applied to COUP Favata+2005)



Unlike the solar case, the extended coronal structure we see on stars are of greater scales than ever seen on the Sun- beyond the closed corona, beyond corotation. Sometimes they occur on stars with close-in dust disk truncation radii, most of the time they aren't (disk is thought to inhibit formation of large structure, possibly by compressing or stripping coronal field)

Using solar magnetic field models, we validate large loops a posteriori

Images courtesy of UCAR's High Altitude Observatory and Rhodes College.



Source = NASA SDO youtube channel: http://youtu.be/8dTM-UJvvEY

A very large and bright prominence erupted off the surface of the Sun around 19:00 UT on August 31, 2012 and just kept going. This video from the STEREO Behind spacecraft shows the prominence and the coronal mass ejection (CME) in which its is embedded as it leaves the Sun (orange, EUVI) and travels through the fields of view of COR1 (green), COR2 (red), and HI1 (blue) telescopes before it finally disappears from HI1 around the end of September 2, still clearly visible more than two days after it erupted. While CMEs are routinely seen in the Heliographic Imager (HI) telescopes, it's very rare for prominences to stay visible for so long. The HI1 field of view ranges from 4 to 24 degrees away from the Sun. To get a sense of scale, we know the Sun is roughly 860,000 miles wide—and look how far the prominence holds together. And this CME is so bright, it initially saturates the COR1 telescope.

Also visible in the movie is the planet Venus, which appears as a bright spot on the right side of the COR2 field. Venus is extremely bright and its image is saturated on the COR2 detector. It also creates a couple of artifacts in the movie due to internal reflections within the HI1 telescope. The first of these artifacts is a loop-like feature near the position of the planet on the left side of the HI1 field. The second is a large bubble-like feature on the opposite side of the HI1 image--this is more easily seen at the start of the movie. Both of these artifacts are explained on our website at http://stereo.gsfc.nasa.gov/artifacts/artifacts_reflections.shtml

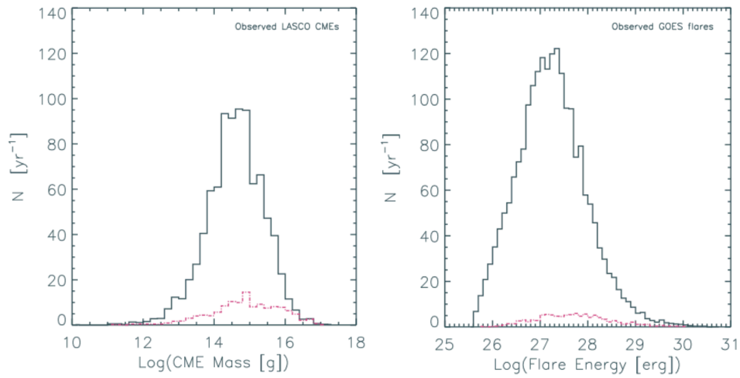
Ramifications

- Activity can impact planet formation
  - Chondrule formation via shock heating of CME hitting disk- Miura & Nakamoto (2007)
  - Composition of disk
- Strong early winds, frequent CMEs
  - Atmospheric stripping
  - oxidation, chemistry changes
- Stellar rotation evolution

Shock-heating formation of chondrules: Miura & Nakamoto, 2007 (Icarus)
Hot jupiters
http://iopscience.iop.org/0004-637X/738/2/166/fulltext/
Terrestrial planets
http://online.liebertpub.com/doi/abs/10.1089/ast.2006.0127
Tidal forces on hot jupiter magnetospheres
http://adsabs.harvard.edu/abs/2011ApJ...728..152T
Evghenya Schkolnik- Ca II line variability as indicators of planet-star magnetic interaction
http://adsabs.harvard.edu/abs/2008ApJ...676..628S

Solar Flares and CMEs

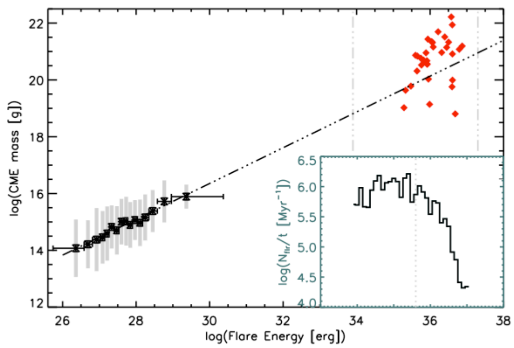
- Correlated 11 years of LASCO, GOES data



Aarnio et al. (2011)

Solar CMEs → Stellar CMEs

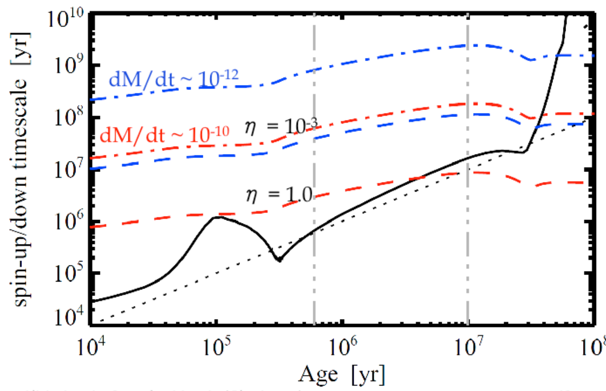
- Post-flare loops: 10^{19}-10^{22} g
- Our stellar CME mass loss rates: ~10^{-9} – 10^{-11} $M_{\odot}$/yr



Aarnio, Matt & Stassun (2012)

Mass loss, slowing stellar rotation?

- Angular momentum problem
- Mass lost from extended lever arm
- Torque ~ r^2



Aarnio, Matt, & Stassun (2012 ApJ)

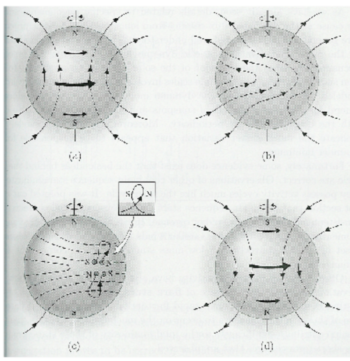
Summary

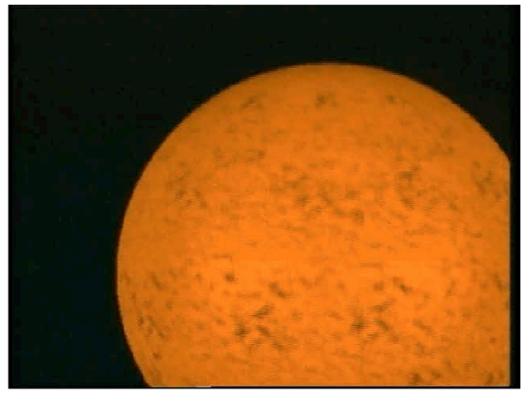
- Physics of solar flares informs understanding of stellar flares
- Astrophysical methods applied to solar data yields new insight
- Studying Suns in time tells us how solar system came to be

Resources for additional information

- Solar Dynamics Observatory (SDO) http://sdo.gsfc.nasa.gov/
- Solar and Heliospheric Observatory (SoHO) http://sohowww.nascom.nasa.gov/
- Solar and TErrestrial RElations Observatory (STEREO) http://www.nasa.gov/stereo/
- Transition Region And Coronal Explorer (TRACE) http://trace.lmsal.com/
- http://spaceweather.com
- Mac SDO gadget: The Sun Now
- NASA 3D Sun: iOS app, gives alerts when flares happen

The Solar Cycle: Dynamo at Work





11/10/12 Alicia Aarnio, Saturday Morning Physics 46

Backup slide not shown in talk, giving an overview of the solar dynamo. Solar cycle figure: Roger Tayler, The Sun as a Star. Movie credit: http://sohowww.nascom.nasa.gov/gallery/Movies/animations.html
We're going to go inside the Sun now, and follow the path of magnetic flux from inside to out.
I. Field is created, amplified, where the convective zone/radiative zones meet
Magnetic field is 'frozen in' to the plasma; this results in a twisting effect as the sun rotates faster at the equator than at the poles. After 11 years, the twisted 'skin' is shed, and the poles reverse orientation- lather, rinse, and repeat.

Simplistically speaking, the dynamo (motion of charged particles in the sun's interior) is responsible for the sun's magnetic field. These particles are moving due to convection… moving plasma can influence the magnetic field as well. Eddy currents in the plasma can sweep the magnetic field clear of a convective cell and concentrate it in flux ropes at the edges. If convection is modeled as a system of eddies, the magnetic field in the convection zone may be concentrated into buoyant flux ropes which rise towards the surface and this in turn may be related to the appearance of sunspots.
Dynamo is caused by both large scale rotation motion (differential) and smaller scale convective motion.