Chandra X-ray, HST optical, Spitzer IR
NGC602 in the SMC
d=60pc
Radiation Processes

Thermal plasma:
- Black-body (neutron stars and hottest WD). Continuum.
- Collisional ionized plasma (stellar coronae). Lines
- Photoionized plasma (close to BH and NS). Lines
- Thermal bremsstrahlung. Continuum

Non-thermal plasma. Mainly continuum.
- Synchrotron.
- Inverse Compton
- Non-thermal bremsstrahlung

When X-ray radiation is produced (by any of the processes above), X-ray photons travel through the medium and interact with it. Always present: absorption in the ISM
X-rays from Stars

NASA/EIT/W.Waldron, J.Cassinelli
Brief reminder: Stars

Low-mass stars on main sequence:
- pp-cycle $\rightarrow \epsilon \sim T^6$
- Radiative equilibrium core
- Large temperature gradient outwards
- Outer convection envelopes
- Weak stellar winds

Massive stars on main sequence:
- CNO-cycle $\rightarrow \epsilon \sim T^{15}$
- Convective core
- Outer radiative envelopes
- Strong stellar winds

http://chandra.harvard.edu/photo/2005/neon/

<table>
<thead>
<tr>
<th>Sp</th>
<th>$T_{\text{eff}}$</th>
<th>H$\beta$</th>
<th>Other Features</th>
<th>$M/M_\odot$</th>
<th>$R/R_\odot$</th>
<th>$L/L_\odot$</th>
<th>T(MS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>$&gt;33000$</td>
<td>weak</td>
<td>He$^+$, mb. emission</td>
<td>$&gt;20$</td>
<td>$&gt;10$</td>
<td>90,000-800,000</td>
<td>10-1 Myr</td>
</tr>
<tr>
<td>B</td>
<td>10,500-30,000 K</td>
<td>med.</td>
<td>HeI absorption</td>
<td>3-18</td>
<td>3.0-8</td>
<td>95-52,000</td>
<td>400-11 Myr</td>
</tr>
<tr>
<td>A</td>
<td>7,500-10,000 K</td>
<td>strong</td>
<td>H lines</td>
<td>2-3</td>
<td>2-3</td>
<td>8-55</td>
<td>3Gyr - 440 Myr</td>
</tr>
<tr>
<td>F</td>
<td>6,000-7,200 K</td>
<td>med.</td>
<td></td>
<td>1-2</td>
<td>1-1.5</td>
<td>2.0-7.0</td>
<td>7-3 Gy</td>
</tr>
<tr>
<td>G</td>
<td>5,500-6,000 K</td>
<td>weak, Ca+ H</td>
<td>K, Na ”D”</td>
<td>0.9-1</td>
<td>0.8-1</td>
<td>0.6-1.5</td>
<td>15-8 Gy</td>
</tr>
<tr>
<td>K</td>
<td>4,000-5,250 K</td>
<td>v. weak</td>
<td>a+, Fe, CH,CN</td>
<td>0.6-0.8</td>
<td>0.6-0.80</td>
<td>0.10-0.4</td>
<td>17 Gy</td>
</tr>
<tr>
<td>M</td>
<td>2,600-3,850 K</td>
<td>TiO, mol.</td>
<td></td>
<td>0.08-0.5</td>
<td>0.2-0.6</td>
<td>0.001-0.08</td>
<td>56 Gy</td>
</tr>
<tr>
<td>L</td>
<td>2,600-3,850 K</td>
<td></td>
<td>Brown dwarfs</td>
<td>&lt;0.08</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Sp: spectral type
H$\beta$: strength of H$\beta$
Other Features: other distinctive features
M/M$_\odot$: mass relative to the Sun's mass
R/R$_\odot$: radius relative to the Sun's radius
L/L$_\odot$: luminosity relative to the Sun's luminosity
T(MS): time on main sequence

Brown dwarfs: masses below the Sun's mass, not on the main sequence.
Magnetic fields

The Sun by Soft X-Ray Telescope on the Yohkoh spacecraft

After 5 billion years, the Sun is still popping and boiling, unable to settle down into the decadent middle age that simple theoretical considerations would suggest. (...) It appears that the radical element for the continuing thread of cosmic unrest is the magnetic field. (E N Parker, Cosmical Magnetic Fields, 1979)

Direct measurements of magnetic fields: photosphere Magnetic field plays a minor role in the photosphere Magnetic field dominates in the corona: X-rays coronal heating, flares, CMEs, wind acceleration
\(\alpha\Omega\)-Dynamo

The Parker mechanism has been mathematically formalized and generalized by mean-field theory (Krause, Rädler, Steenbeck 1966). Evolution of a suitably averaged magnetic field in a turbulent flow of an electrically conducting fluid.

\[
\frac{\partial\langle B \rangle}{\partial t} = \nabla \times (\langle u \rangle \times \langle B \rangle + \alpha\langle B \rangle) - \nabla \times [(\eta + \beta)\nabla \times \langle B \rangle]
\]

\(\alpha\langle B \rangle\) drives a mean current parallel or anti-parallel to the mean magnetic field.

\(\alpha\)-effect generates a meridional field from an azimuthal and vertical.

\(\Omega\)-effect describes differential rotation, \(\Omega\) is angular velocity.

\(\alpha \frac{\partial \Omega}{\partial r}\) describes dynamo waves.

Mean-field \(\alpha\Omega\)-dynamo reproduces many of the key features of the solar cycle: the periodic field reversals, the polarity of sun-spot groups, the equatorwards drift of the activity zones.

However the equatorwards drift requires radially inward fast increase of the angular velocity. This is in direct conflict with the results of helioseismology.
**Ω-effect**

Differential rotation - the change in rotation rate as a function of latitude and radius within the Sun.

Magnetic field is stretched out and wound around the Sun.

Latitudinal differential rotation can wrap magnetic field line around the Sun in about 8 months.

http://solarscience.msfc.nasa.gov/
Effect of rotation on the rising "tubes" of magnetic field- loops look like letter $\alpha$.

$\alpha$-effect governs tilt of spot groups and polarity reversal.

Similar effects are observed in solar type stars, so Sun is an average star.

Dynamo operates in all low- and solar-mass stars. Activity scales with rotation rate.

http://solarscience.msfc.nasa.gov/
Solar dynamo

Observational laws: 1) 11-year period; 2) butterfly diagram; 3) tilt of sunspot group; 4) 22-year magnetic cycle
Magnetic fields and temperature distribution

Convection brings the magnetic field lines on the surface. Lines are always closed, the relative role of gas and magnetic field pressure changes with height.
Lower corona: now and then

SOHO images in Fe IX/X 171Å line. Lower corona, plasma temperature 1MK.
Flares

Solar flares are an explosions in the solar atmosphere:
Sudden bursts of particle acceleration, plasma heating, and bulk mass motion.
Release of energy stored in the magnetic fields that thread the corona.
In the largest flares $>10^{32}$ ergs can be released in a few minutes.
Largest flares observed around solar maximum
There is a continuous spectrum of flare sizes $dN/dE = kE^{-\alpha}$, $\alpha = 1.6 \ldots 2.6$

No consistent theory of flares
Reconnection, 3D-topologies
How corona is heated?

Coronal activity scales with magnetic activity, 11 yr cycle
Corona never disappears:

\[ L_X = 10^{26} \text{ erg/s in min activity, } 10^{27} \text{ erg/s in max activity} (+ \text{ very strong flares}) \]

The energy release mechanism is magnetic in origin - but, what specific heat input is dominating in a given coronal feature throughout the solar cycle?

Leading theories:

* Sound wave dissipation (Walsh & Ireland 2003)
* Differential heating by plasmakinetic processes (Vocks & Marsch 2002)
* Nanoflare heating: small scale reconnection events (Parker 1988)

Model shall describe physical conditions in the corona:

**density, temperature, velocity**

Corona heating and dynamo theory should be consistent
Sun offers only a limited range of parameters.
Solar-Stellar connections

All low- and solar-type stars possess magnetic fields and are X-ray active.

Is Sun an average star?
The Sun in time?

How dynamo and heating processes differ among stellar types?

In some cases, the magnetic field can be directly measured through the Zeeman effect, but in general X-ray emission is used to infer stellar activity.

In accordance with dynamo theory the magnetic activity of cool stars is related to their rotation rate: faster spinning stars are more active ($\alpha$-effect increases with rotation rate).

For solar type stars ($M < 1.5M_\odot$) and ages of $> 100$ Myr, angular momentum loss by a stellar wind brakes rotation: rotation nearly uniquely determined by the stellar age.

Late type stars, M and brown-dwarfs are fully convective. How their activity level differ from solar-type stars?
X-ray observations overturn accepted Dynamo models

Wright & Drake, Nature, 16

- Dynamo operates in tachocline
- Fully convective stars → no tacholine
- Predicted, MV should be different in X-rays from GV
- Not observed
- Ergo, dynamo operates in the convective zone
Coronal activity cycles in solar analog stars

The Sun 11-yr cycle is the global manifestation of its activity.

The behavior of HD 81809 (G2 + G9) is a simple extension of the solar case.

Two more studied stars show cyclic activity as well.

Fig. 3. Evolution of the X-ray surface flux (in the 0.2–2.5 keV band) of HD 81809 from April 2001 to May 2007. The typical X-ray surface flux of the Sun at minimum and maximum of the cycle, in the ROSAT band, is also plotted.

Fig. 4. The evolution of the coronal X-ray temperature and luminosity along the cycle in both the Sun (crosses) and HD 81809 (triangles).
## Young stars (solar type)

<table>
<thead>
<tr>
<th>Properties</th>
<th>Infalling Protostar</th>
<th>Evolved Protostar</th>
<th>Classical T Tauri Star</th>
<th>Weak-lined T Tauri Star</th>
<th>Main Sequence Star</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sketch</td>
<td><img src="image1.png" alt="Sketch" /></td>
<td><img src="image2.png" alt="Sketch" /></td>
<td><img src="image3.png" alt="Sketch" /></td>
<td><img src="image4.png" alt="Sketch" /></td>
<td><img src="image5.png" alt="Sketch" /></td>
</tr>
<tr>
<td>Age (years)</td>
<td>$10^4$</td>
<td>$10^5$</td>
<td>$10^6 - 10^7$</td>
<td>$10^6 - 10^7$</td>
<td>$&gt;10^7$</td>
</tr>
<tr>
<td>mm/Infrared Class</td>
<td>Class 0</td>
<td>Class I</td>
<td>Class II</td>
<td>Class III</td>
<td>(Class III)</td>
</tr>
<tr>
<td>Disk</td>
<td>Yes</td>
<td>Thick</td>
<td>Thick</td>
<td>Thin or Non-existent</td>
<td>Possible Planetary System</td>
</tr>
<tr>
<td>X-ray</td>
<td>?</td>
<td>Yes</td>
<td>Strong</td>
<td>Strong</td>
<td>Weak</td>
</tr>
<tr>
<td>Thermal Radio</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Non-Thermal Radio</td>
<td>No</td>
<td>Yes</td>
<td>No ?</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Feigelson & Montmerle ARAA 37, 363
Observations

DG Tau $M = 1M_{\text{sun}}$, $\text{Age}=1\text{Myr}$
Jets, disk absorption, flares
Accretion and corona (?)
Importance for planet formation
HST & Chandra: Pillars of Creation in M2

http://chandra.harvard.edu/2007/m16/
Massive stars in the center of Orion nebula
Young (1Myr) O type stars that ionize the nebula
... Are X-ray sources and they are hard

Massive stars (earlier than A-type)
are fully radiative
Solar type coronae powered by $\alpha \Omega$-dynamo
cannot operate there

Massive stars posses strong stellar winds
The evolution of (very) massive stars

Evolution ← stellar wind (!)

- O and B type stars
- Luminous Blue Variables
- Wolf-Rayet (WR) stars

According to dominant spectral lines

WN (nitrogen) →
WC (carbon) →
WO (oxygen) →
How X-rays are generated in O stars? Leading theories.

- Bow shocks around blobs (Lucy & White '80, Cassinelli et al. '08)
- Magnetically confined loops at the stellar base (Cassinelli & Swank '83)
- Wind shocks from the instabilities of radiation driving (Owocki et al. '83)
- Collisions of dense shells in deep wind regions (Feldmeier et al. '97)
High-Resolution X-ray Spectra

* Overall spectral fitting $\rightarrow$ plasma model, abundances

* Line ratios $\rightarrow$ $T_X(r)$, spatial distribution

* Line profiles $\rightarrow$ velocity field, wind opacity
X-Ray from stars

- Low and solar type stars: magnetic fields
- Magnetic fields reconnection: coronal heating → X-ray
- Young forming stars (T Tauri stars): coronae and accretion
- High-mass stars: stellar wind shocks
X-ray Binaries

http://chandra.harvard.edu/photo/2004/ss433/
53 years of X-ray astronomy

1962 Bruno Rossi & Riccardo Giacconi
American Science & Engineering (AS&E)

A rocket with Geiger counter: to search X-rays from the Moon

Rocket spans - the field-of-view passed a bright source named Scorpius X-1

Sun: X-rays are $10^{-6}$ visible light intensity
Sco X-1: $L_X = 10^9 L_X^{\text{sun}}$

2002: Giacconi receives NP from the king of Sweden

What is X-ray binary?

Binary star where one companion is a NS or BH. The matter is accreted either from the inner Lagrangian point, or from surrounding stellar wind.

Gravitational and kinetic energy of matter falling onto the central object is converted by dissipation to heat.
Neutron stars

- Neutron stars are the collapsed cores of some massive stars. Mass of the Sun in r=10km. Rotation periods 0.001 sec to 2000 sec. B about $10^{12}$ Gs. Density $10^{14}$ g/cm$^3$ GR

- Iron core collapse $\rightarrow$ protons and electrons combine to neutrons plus neutrinos $\rightarrow$ neutron star.

- High-density, strong magnetic field: different (from 'normal') atomic structure

- Born very hot, cools by neutrino radiation in first moments. Rotation is slowed down by magnetic torque.
A black hole is a region of space that has so much mass concentrated in it that there is no way for a nearby object to escape its gravitation.

Einstein GR → Karl Schwarzschild: a mathematical solution to the GR equations that described such an object.

- In GR, gravity is a manifestation of the curvature of spacetime.
- **Event horizon**: the escape velocity = the velocity of light
- Inside of the horizon, spacetime is distorted so much that the coordinates describing radial distance and time switch roles.
Accretion

The depth of potential well in compact objects is large → large ammount of energy is liberated in accretion process.

The process of accretion at a rate $\dot{M}$ onto an object of mass $M$ and radius $R$ gives a luminosity of

$$L = \frac{GM\dot{M}}{R}$$

Heat is partially radiated out, partially converted to work on the disc expansion and (in the case of BH accretion) partially lost inside the hole.

Mass to energy conversion efficiency $\eta = L/Mc^2 = 0.1 \rightarrow$ considerably greater than the efficiency of nuclear fusion.
**Eddington limit**

The accretion rate is limited by the Eddington limit. Defined by the balance between outward radiation pressure and inward gravitational force.

Any phenomenon lasting more than a few dynamical scales should have $L < L_{\text{edd}}$.

Force of radiation acting on an electron

$$F_{\text{rad}} = \frac{L}{4\pi R^2 h \nu} \sigma_T \frac{h \nu}{c}$$

Force of gravity on a proton

$$F_{\text{grav}} = \frac{G M m_p}{R^2}$$

$$L_{\text{edd}} = \frac{4\pi G M m_p c}{\sigma_T} \approx 10^{38} M$$

Maximum accretion rate
**Accretion disks**

Matter’s angular momentum is greater than the Keplerian angular momentum, so accreting matter will orbit a compact object.

Dissipation and friction: matter flattens and spreads equatorially into an accretion disk. The angular momentum is transported outward by friction and mass moves inward.

**Newtonian gravity**: angular momentum at a distance $R$ from a spherical object with the mass $M$ is $(GMR)^{1/2}$, monotonically increasing stability of all orbits.

**Einstein gravity**: angular momentum has a minimum at the radius of the innermost stable circular orbit (ISCO). Orbits above $r_{ISCO}$ are stable, and below are unstable.

For a non-rotating black hole $r_{ISCO} = 6GM/c^2$
Spherically symmetrical (Bondi) accretion

- Spherical accretion onto an object occurs e.g. in a star accreting from ISM or in a compact object immersed in stellar wind.

- This happening when angular momentum is not dynamically important

- Accretion rate \( \dot{M}_{\text{acc}} = 4\pi r_A^2 \rho v \), velocity can be either sound speed (\( c_s \)) or motion speed of compact object through the medium.

- Accretion \( E_{\text{tot}} < 0 \rightarrow r_A \) is effective radius such that escape velocity

\[
\sqrt{\frac{2GM}{r_A}} = v
\]

\[
\cdot \quad r_A = \frac{2GM}{v^2} \quad \rightarrow \quad \dot{M}_{\text{acc}} = \frac{8\pi \rho G^2 M^2}{v^3}
\]
Accretion of stellar wind on a neutron star
X-ray Binary Classification

Classified according to the type of donor

- **High-mass X-ray binaries (HMXB):** early-type star (OB or Wolf-Rayet). Stellar wind accretion. Located in star forming regions. *Cyg X-1, Vela X-1, Her X-1*

- **Low-mass X-ray binary (LMXB):** late type stars. Mass transfer via L1. Many types. Trace old population, globular clusters. *Sco X-1*
- The rotation rate of the NS is held near equilibrium, depending on the $B_0$ and rotation rate.
- If NS is spinning too fast $R_M > R_{sy}$, matter cannot fall through the magnetosphere.
- Material is flung out of the system, inducing a braking torque. Spin-down of a pulsar long period pulsars.
- If is spinning too slow $R_M < R_{sy}$. Density gradient in stellar winds $\rightarrow$ a side closer to the star accretes more $\rightarrow$ a torque $\rightarrow$ spin up millisecond pulsars.
Persistent HMXBs

- OB-type donor (usually a supergiant). NS is immersed in a stellar wind. Orbital separation is typically $2R_{\text{star}}$.

- Some host X-ray pulsars
- Sensitive to the properties of donor winds
- About a dozen known in the Galaxy

**Fig. 4.**—A model for the system Cen X-3/Krzeminski’s star during the turn-on of 1972 July.

Hatchett & McCray 1977
X-ray spectra

- Strongly absorbed power-law
- Absorption depends on orbital phase
- Compact object distorts wind
- X-ray field distorts the wind
Besides X-ray pulses, flares and off-states are observed in HMXBs

Bozzo et al. 2011
Roche Lobe filling HMXB

High $L_x > 10^{38}$ erg/s; hard and soft spectral states; Cyg X-1 black hole
1. Blue supergiants
2. Red Supergiant
3. Supernova
4. Black hole
5. Accretion disc, with matter stolen from HDE 226868. HDE 226868 is now more massive due to supernova.
6. HDE 226868 in red supergiant stage. X-ray emission is intense at this period.
7. HDE 226868 goes supernova.
8. Binary black hole system?

SS 433: the central engine is obscured by the accretion disc and only jet is visible in X-rays
43  Tolman-Oppenheimer-Volkoff (TOV) limit

The Chandrasekhar limit

- The maximum nonrotating mass which can be supported against gravitational collapse by electron degeneracy pressure. \(1.4 \text{M}_{\odot}\)

The Tolman-Oppenheimer-Volkoff limit

- The maximum nonrotating mass which can be supported against gravitational collapse by short-range repulsive neutron-neutron interactions mediated by the strong force and also by the quantum degeneracy pressure of neutrons \(1.5...3.0 \text{M}_{\odot}\)

- Quark degeneracy: At densities greater than those supported by neutron degeneracy.

- Strange matter is a degenerate gas of quarks that contain strange quarks in addition to the usual up and down quarks.

- **Quark stars:** formed by the collapse of objects above the TOV mass limit for neutron-degenerate objects.
45 Black Hole X-ray Binaries

Oppenheimer & Snyder (1939): formation of a black hole.

- 20 XRBs contain a compact object with $M > 3M_\odot$. In the Galaxy $10^{8-9}$.

- A BH is specified by $M$ (scale) and spin $a = J/c M$ (geometry), where $J$ is angular momentum. Or $a^* = a/R_G$.

  - Schwarzschild BH: $a^* = 0$; Kerr BH: $a^* = 1$.

- Event horizon of a Schwarzschild BH $R_S = 2R_G = 30\text{km} \ (M/10M_\odot)$, the ISCO lies at $R_{\text{ISCO}} = 6R_G$, and the maximum orbital frequency is $v_{\text{ISCO}} = 220\text{Hz}(M/10M)^{-1}$. For Kerr BH ($a^* = 1$), the $R_S = R_{\text{ISCO}}$ and $v_{\text{ISCO}} = 1615\text{Hz}(M/10M)^{-1}$.

- Radiating gas orbiting a compact object is the steady-state, thin accretion disk model (Shakura & Sunyaev 1973) → $T(R) \propto R^{-3/4}$. Luminosity of an annulus $L_X \propto RdR\sigma_{sb}T^4 \propto R^{-2}$. X-rays are the best window to the horizon of a BH.
46 Census

LMC X-3 B3V
$M_{BH} = 5.9-9.2M_\odot$

LMC X-1 O7III
$M_{BH} = 4.0-10.0M_\odot$

GRS1915+105 MIII
$M_{BH} = 10.0-18.0M_\odot$

Cyg X--1 O9.7I
$M_{BH} = 6.8-13.3M_\odot$

V404 Cyg K0III
$M_{BH} = 10.1-13.4M_\odot$

XTE1118 M0V
$M_{BH} = 6.5-7.2M_\odot$

steady X-ray bright
transient X-ray novae
X-ray binaries: HMXBs, (LMXBs)

Very complex systems: relativity, stellar physics, stellar and galactic evolution, hydrodynamic, etc. etc.

- Matter in extreme conditions
- Stellar winds from massive stars

Neutron stars (X-ray pulsars) - Black Holes