Astronomy 330

Lecture 4

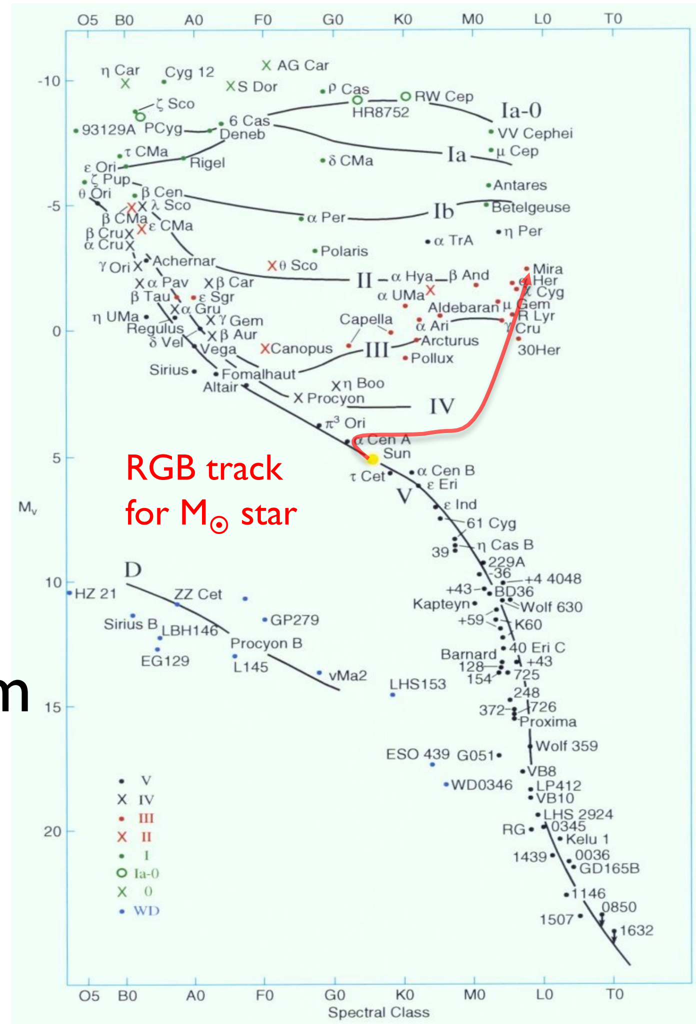
15 Sep 2010

Outline

- Review
  - Stellar evolution/nucleosynthesis/H-R diagrams
    - Reading: "Old Main Sequence Turnoff Photometry in the Small Magellanic Clouds" Noël et al. (2007, AJ, 133, 2037)
      - What is the data they use?
      - Compare Figures 3 and 7 to some of the CMDs in the previous lecture notes – what are the similarities and differences?
- Phases of the Interstellar Medium
- Star-formation & Feedback

Review

- Stellar types:
  - Classification – photometry & spectroscopy
  - τ_{MS}
- Stellar evolution:
- Burning phases
- Paths in the HR diagram (tracks)
- Elemental yields
- Metrics of evolution



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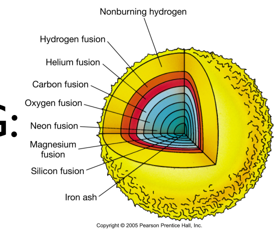

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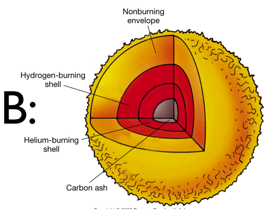

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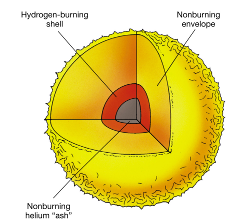
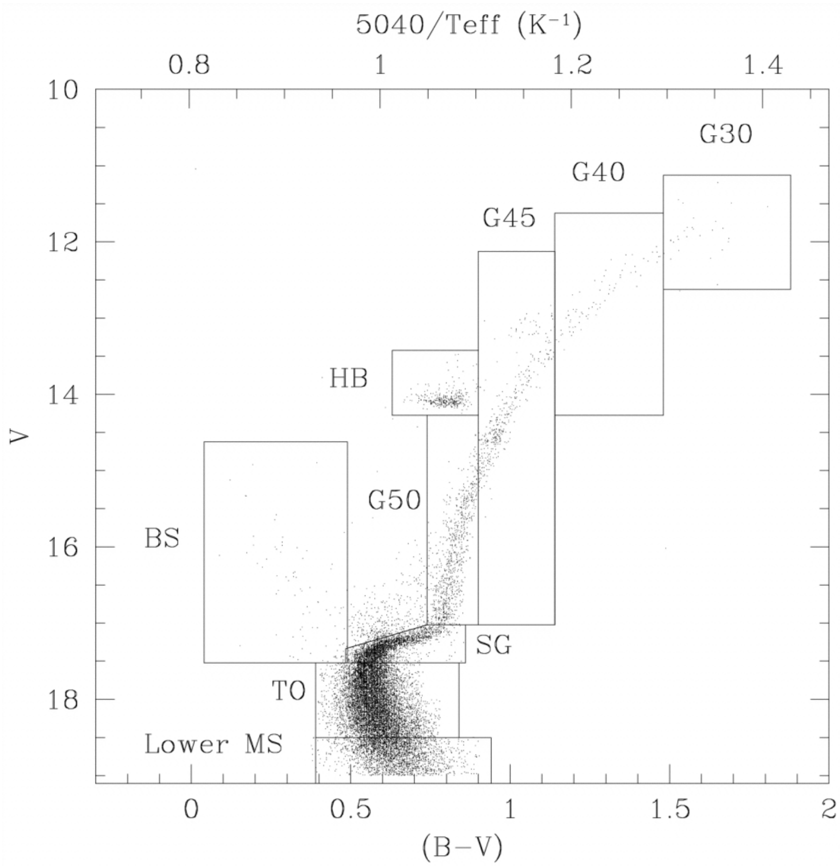
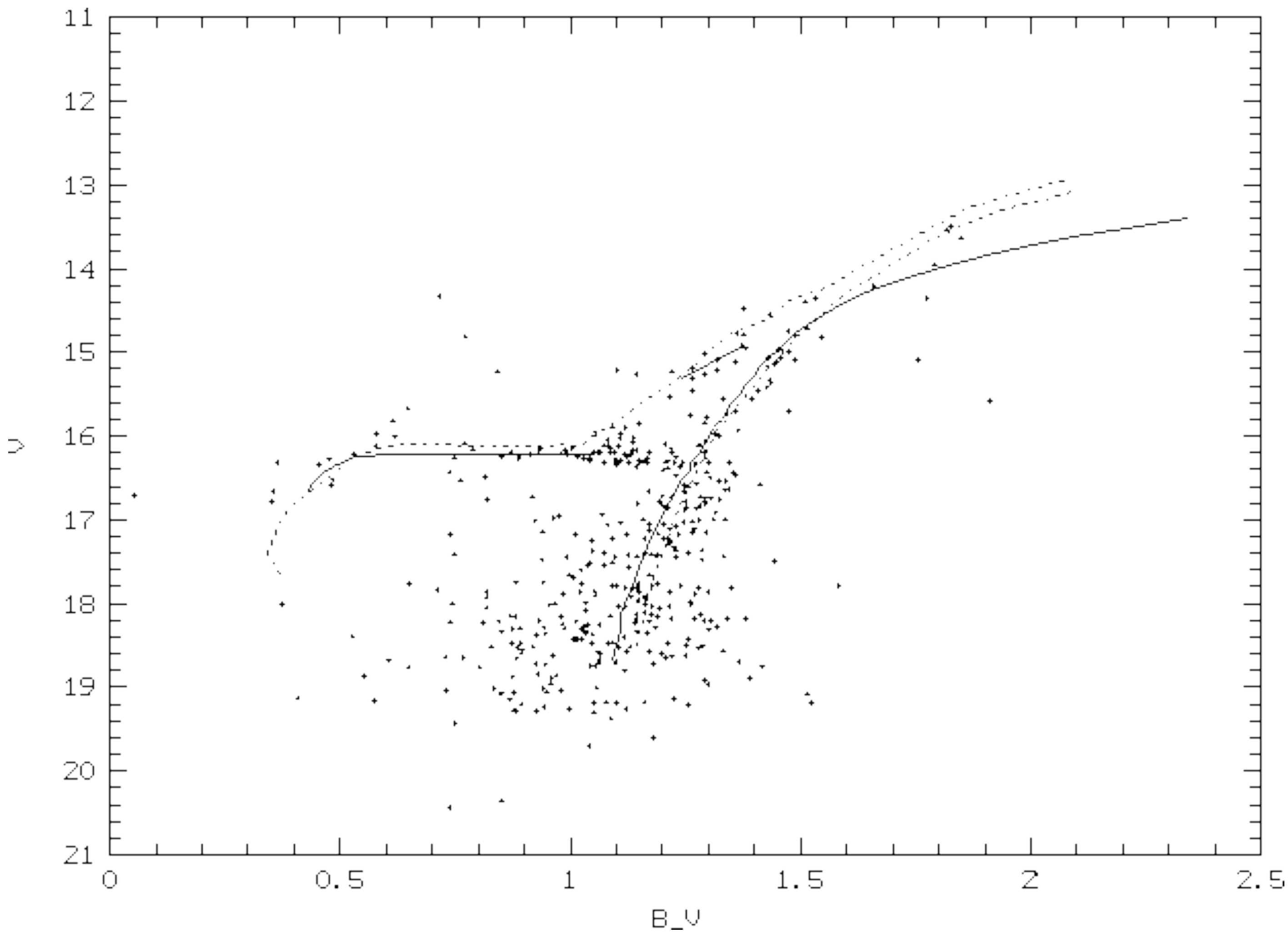


Review



H-R diagram for 47 Tuc

- Evolution + nucleosynthesis – each box is a different burning stage
- Could you sketch the H-R diagram of this cluster and label all of the major burning stages?



11
12
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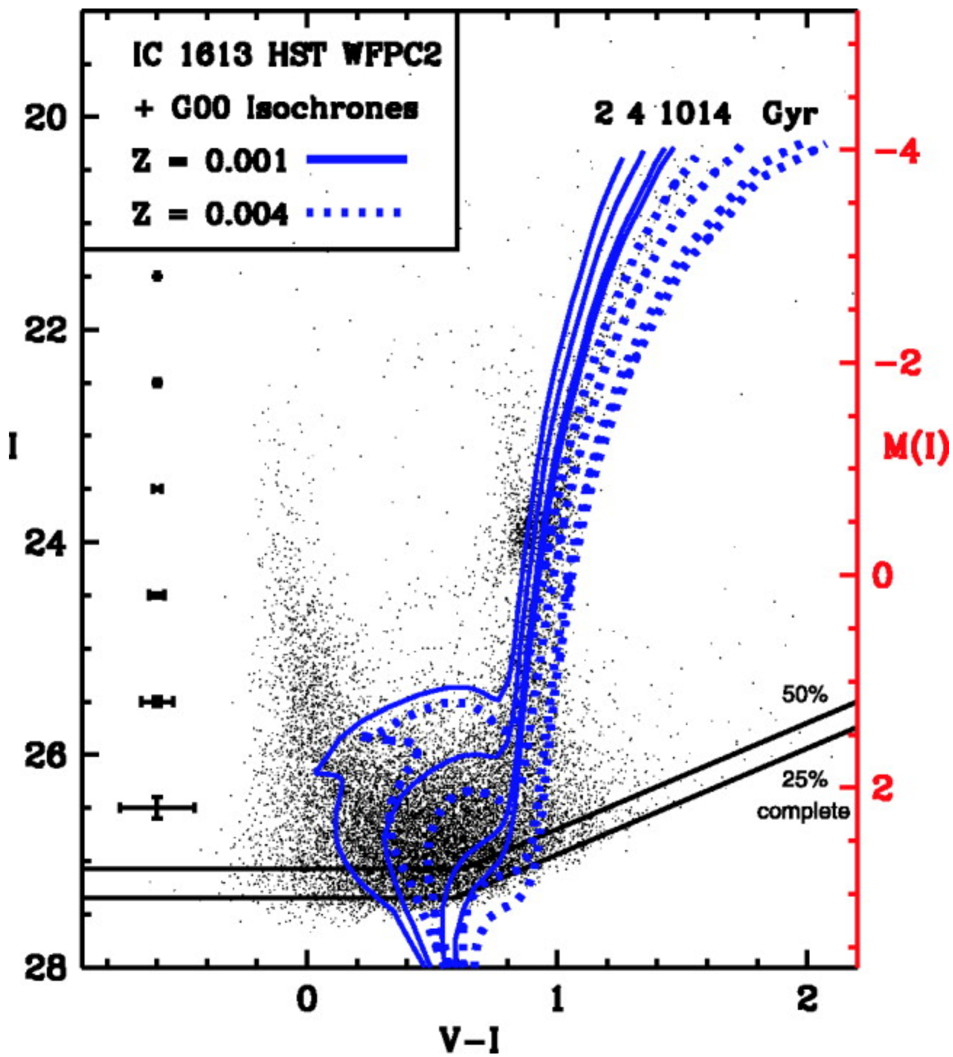
2.5
B_V

H-R Diagram



- Gets more complicated with a mixed-age stellar population
- Multiple turn-offs, multiple HBs
- Dwarf spheroidal galaxies are ideal labs for this

Statistical Stellar Astrophysics

- Stellar initial mass function
  - $dN = N_o \xi(M) dM$
  - $N_o \int dM\, M\, \xi(M)$ = total mass of burst/episode
  - Observationally: $\xi(M)$ goes as $(M/M_\odot)^{-2.35}$
    - "Salpeter IMF"
    - Slight variation with mass (time? environment?), according to some
    - Upper mass limit in the 80-120 $M_\odot$
      - but note small-number statistics become important
    - Turn-over likely below 0.1 $M_\odot$

Stellar Populations

- Integrated Colors
  - Population I – "Disk Population" – open clusters, circular orbits, confined to a disk, "blue"
  - Population II – "Halo Population" – globular clusters, large random velocities, elliptical orbits, spherical distribution, "red"
  - Population III – extremely metal poor, not yet detected
    - Cosmic Mystery #2: Where are the Pop-III stars?
- Correlations
  - Color vs kinematics
    - Blue stars are disk-like
  - Color vs metallicity
    - Red stellar populations tend to be metal poor, strong Galactic correlation between kinematics and metallicity

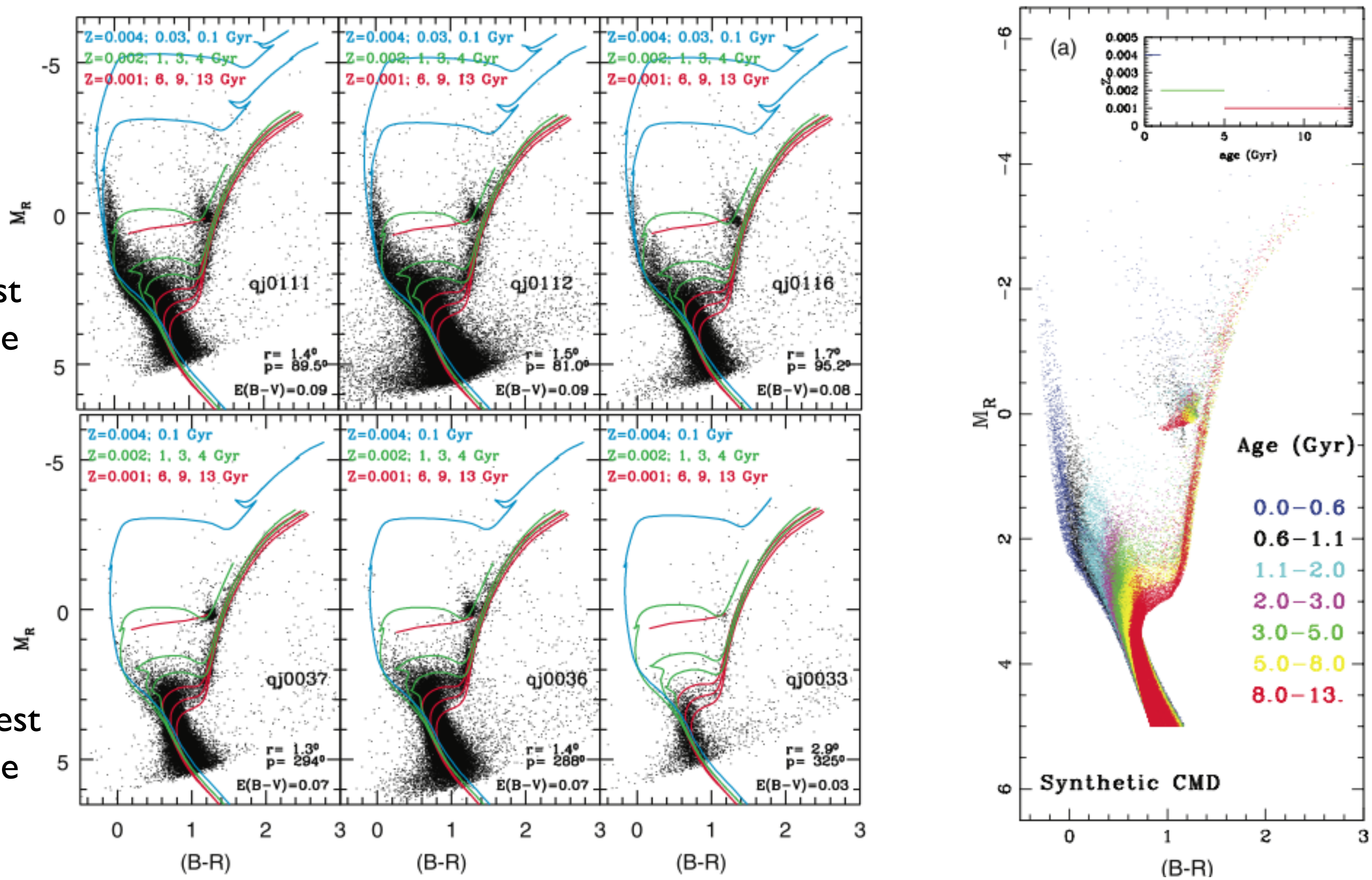
Interpretting CMDs

- Density of any locale on a CMD is a function of IMF, SFR, mass, and age
  - $C(M_V, V\text{-}I) = \iint \xi(\log m, t) \times SFR(t)\, dt\, d\log m$
    - Small mass bin (i.e. single mass)
    - Constant IMF (ξ)
    - Can recover star formation history from a complex CMD
- Statistical Approach
  - What is the probability that a certain distribution of points on the CMD came from one particular set of stellar evolution models (Tolstoy & Saha 1996)

SMC: Noel et al. 2007

East side

West side



Interstellar Matter (ISM)

- Optically visible components
  - Dark band through center of the MW (absorption)
  - Diffuse emission regions
  - Reflection nebulae
- Verification
  - Cluster diameter vs luminosity distances
  - Non-varying absorption lines in binaries

NGC 891 – viewed edge-on

Phases of the ISM

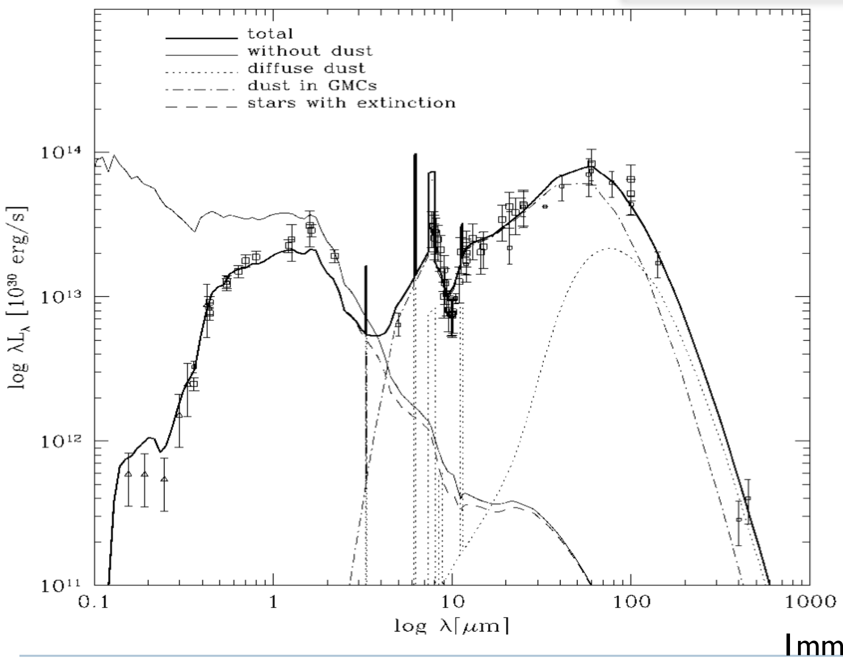
Phase	Temp (K)	N (cm^{-3})	Filling factor	Diag.
Cold	10	10^4	low	CO, mid-IR
Cool	10^2-10^3	10^3	low	HI
Warm	10^3-10^4	10^2	high	HI
Warm	10^4	10	high	$H\alpha$
Hot	10^5-10^6	1	high	X-ray/FUV
Relativistic	?	?	High	Synch.

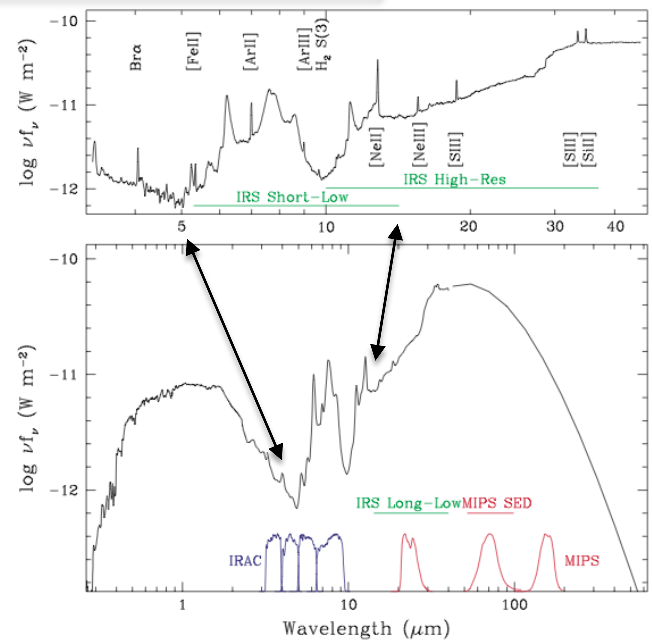
Molecular Gas

- Cold – molecular line spectroscopy with radio/mm wave telescopes.
  - H_2 most common molecule, but no dipole moment, so hard to detect
  - CO next most common molecule; has a dipole moment, transitions due to angular momentum quantum number (e.g. $J=1 \rightarrow 0$ at 2.6mm)
  - $I_{CO} = \int dv\, T_A$ (2.6mm line of ^{12}CO)
    - T_A is the antenna temperature so that $P = kT_A$
  - Conversion to H_2 :
    - $X_{CO} \equiv N(H_2)/I_{CO} \sim 2.3 \times 10^{24}$ (The *infamous* X factor)
    - (is this really the same everywhere???)
  - Other methods include UV spectroscopy to get H_2, even more complex molecules (e.g. HCN)

Dust: The Mid to Far Infrared Window

- What' the difference between dust and molecules?
- Key components:
  - multiple thermal components from 10 to 300 K (cool and cold)
    - 30 microns – 1 mm
  - molecular (PAH) emission
    - 3-30 microns
- Key instruments: IRAS, ISO, Spitzer, and Herschel satellites, SOFIA

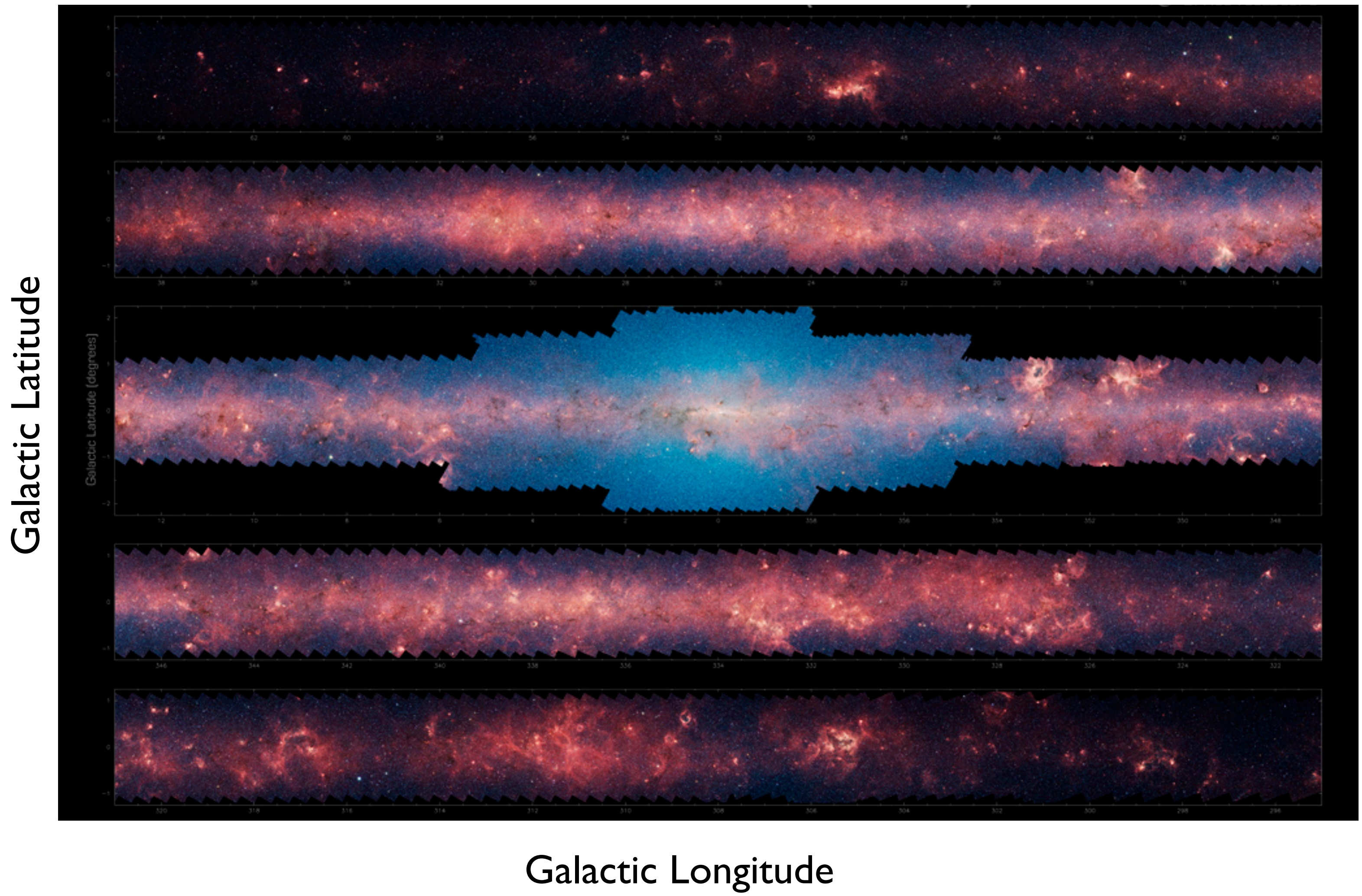


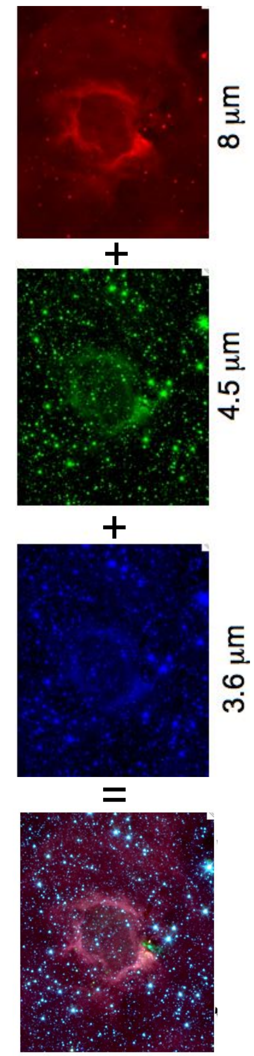


Silva 1998: ISO

Kennicutt et al. 2003: Spitzer

GLIMPSE 3.6 to 8 microns: Stars vs PAH

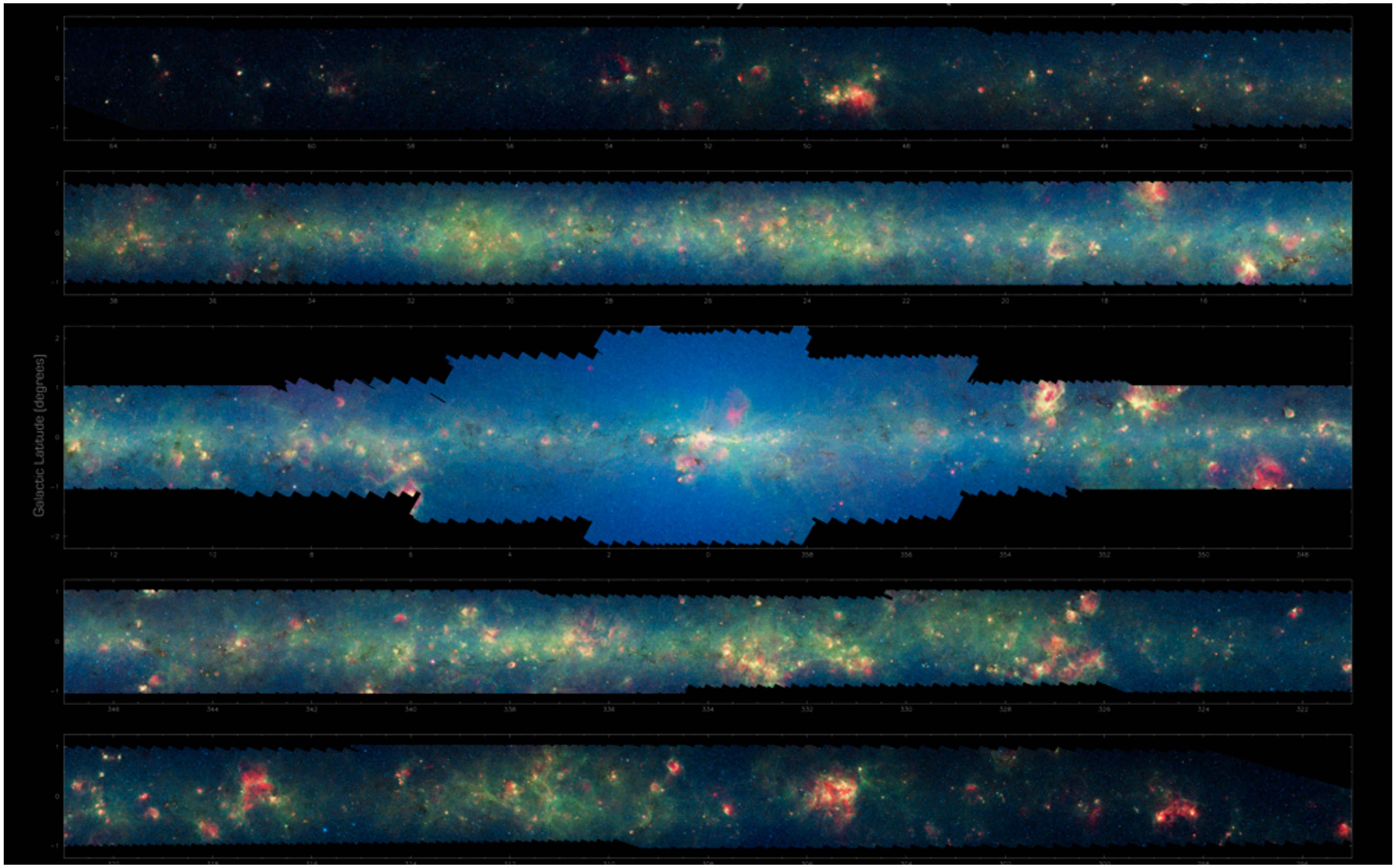


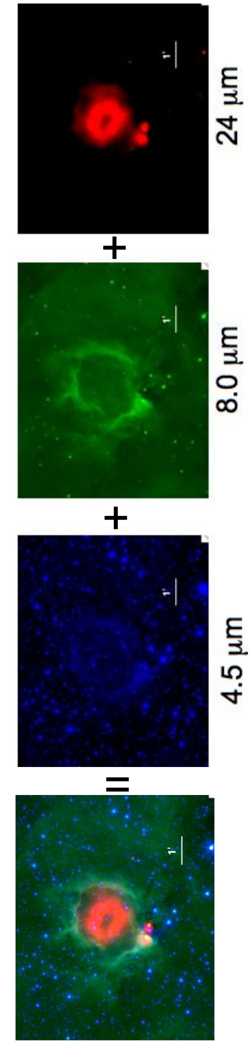


Spitzer Galactic Plane Survey: PI E. Churchwell (U.Wisconsin)

GLIMPSE 3.6 to 24 microns

Galactic Latitude





Galactic Longitude

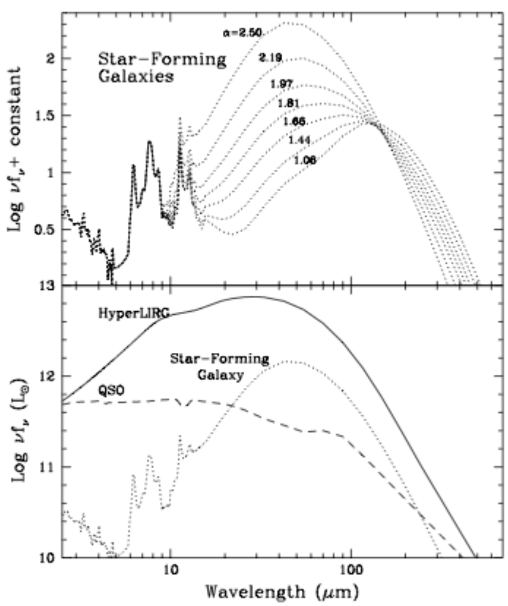
- Dust sub-structure: photo-disassociation regions (PDRs), shocks

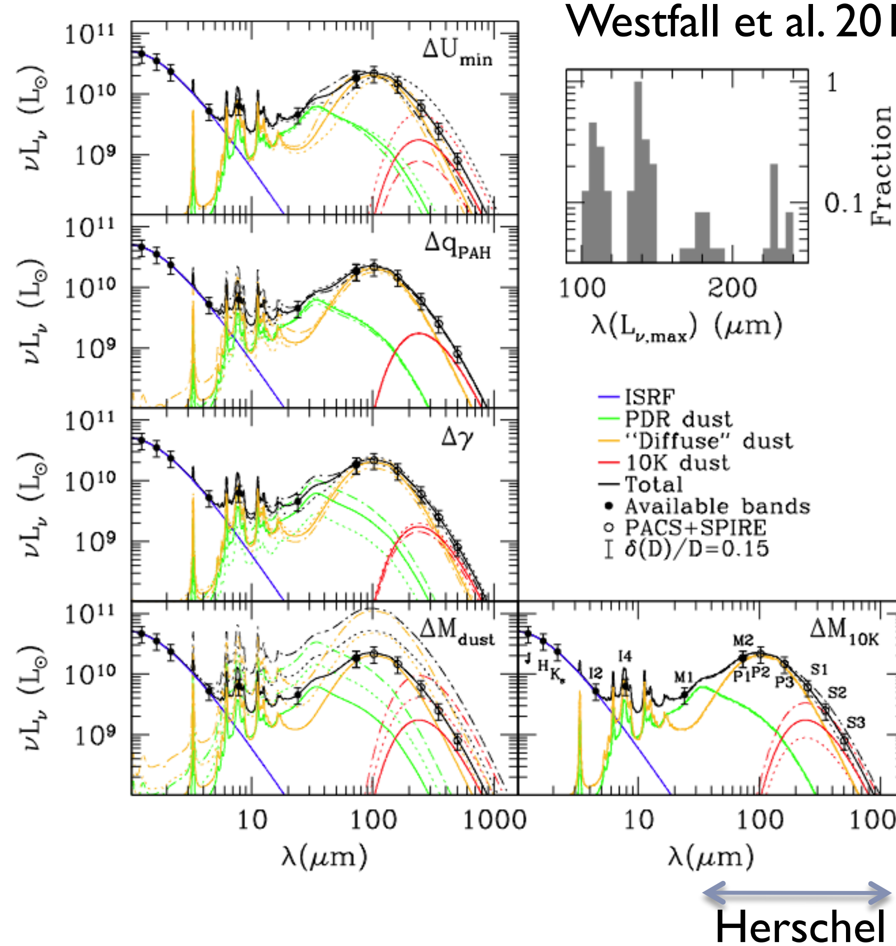
Spitzer Galactic Plane Survey: PI E. Churchwell (U.Wisconsin)

Dust continued

- What drives the detailed shape of the spectrum?
- Radiation field: U
- Composition:
  - PAH abundance q_{PAH}
- Dust Masses: diffuse, PDR
- Temperatures: diffuse, PDR

Westfall et al. 2010





Dale et al 2001

Models: Draine & Li 2007

Dust and Molecules

- Can we estimate molecular gas content from studying the dust?
  - Unsurprising to find tight correlation between I_{CO} and MIR flux, e.g., $I_{24\mu m}$
  - Higher degree of correlation likely to be found by considering broader range of MIR and FIR colors
- Why would we want to do this?
  - CO measurements are hard
  - The conversion from CO to H_2 is frought
  - Detailed modeling of 3-300 micron SEDs* should yield molecular/chemical composition and radiation field:
  - Link to CO measurements to understand X_{CO}
- Research project waiting to happen

*SED = spectral energy distribution

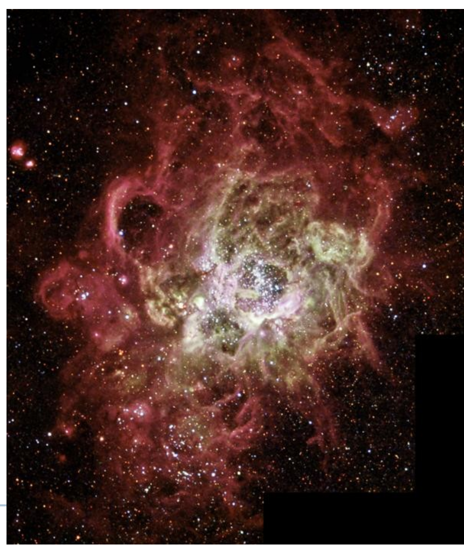
Neutral Hydrogen: 21 cm HI line

- Hyperfine transition in the ground state from the interaction between the spins of the electron and proton.
  - $\Delta E = 6 \times 10^{-6}$ eV → $\nu = 1.4204$ GHz
  - Lifetime of excited level is long (10^7 yr) so collisional excitation and de-excitation is fast compared to spontaneous decay. Level populations depend only on kinetic temperature of the gas.
- Useful relationships:
  - $N_H = 1.82 \times 10^{22} \int dV\, T_B$ (if optically thin)
  - $M_H = 2.36 \times 10^5\, M_\odot \times D^2 \int S(V)\, dV$, where $S(V)$ is in Jy km s^{-1}

Warm Ionized Gas

- Emission from
  - Photoionization
    - We largely see H emission lines via recombination into various primary quantum levels. e.g.,
      - Hα (656.3nm) arises from transition from n=3 to n=2.
      - See example from M33
  - Collisional excitation
    - Forbidden lines
    - C, N, O, Ne, S, Si, Fe

- Line-strengths of H
  ➔ star-formation rates
- Line-ratios of H and forbidden lines ➔ estimates of
  - redenning
  - metallicity
  - T_e = electron temperature
  - n_e = electron density
  - Shocks vs photo-ionization



HII regions: ionizing radiation from OB stars


M33

Estimating Star-formation rates

- Assume:
  - All ionizing photons, $Q(H^0)$, produced by stars
  - Each ionizing photon ionize an atom
  - The rate of ionization is balanced by the rate of recombination (Osterbrock):
- Then:

$$Q(\mathrm{H}^0) = \int_0^{r_s} N_p N_e \alpha_B(T)\, dV$$

  - N_e = number of electrons
  - N_p = number of protons
  - α_B is recombination coefficient (Case B)*
  - r_s = Stromgren sphere
- If $N_e = N_p$ and we take the Ha luminosity to be:

$$L(\mathrm{H}\alpha) = h\nu_{\mathrm{H}\alpha} \cdot \int_0^{r_s} N_p N_e \alpha_{\mathrm{H}\alpha}(T)\, dV$$

- Then the number of Lyman continuum photons is:

$$N_{\mathrm{Lyc}} = L_{\mathrm{H}\alpha} \times 7 \times 10^{11}$$

* Gas is optical thick to ionizing (Lyman continuum) photons

Star-formation rates continued

- Recall Stellar IMF
  - $N_o \int dM\, M\, \xi(M)$ = total mass of burst/episode, $\xi(M)$ goes as $(M/M_\odot)^{-2.35}$
- Young, massive stars (on MS) producing nearly all ionizing radiation
- On MS there is a mass-T relationship
- Integrate IMF weighted by ionizing luminosity per star of mass M to get N_{Lyc}
- Extrapolate integral over full mass of IMF to get total mass
- Current best estimates: K98
  - SFR ($M_\odot$ year^{-1}) = 7.9×10^{-42} L(Hα) (ergs s^{-1}) = 1.08×10^{-53} Q(H^0) (s^{-1})
    - Case B for T_e = 10,000 K
  - SFR ($M_\odot$ year^{-1}) = $(1.4\pm0.4)\times10^{-41}$ L[OII]$_{\lambda3727}$) (ergs s^{-1})
    - empirical
  - In all cases, must correct for extintcion

Can extend to Paschen series where extinction is smaller; see Calzetti et al. (2005)

- Why not measure N_{Lyc} directly?
- What about UV continuum at wavelengths longer than the Lyman limit?
- What about the FIR (what heats the dust)? Radio continuum?

- See: Kennicutt et al.: 1983 1984, 1989, 1998, 2003, 2009; Lee et al. 2009

Stopped here

Line diagnostics

- Redenning:
  - Use recombination coefficients for different lines compared to measured flux ratios, e.g., Hα/Hβ
    - Recombination coefficients depend in detail on knowing T_e and n_e
    - Must correct emission for stellar photospheric absorption which is, e.g. larger in Hβ than Hα
- Temperature: T_e
  - Flux ratios of forbidden-lines from ions with different ionization potentials, e.g.,
    - H^+, S^+, N^+, O^+, O^{++}
    - Metallicity and shock-heating effects
- Density: n_e
  - Flux ratios of some forbidden-line doublets, e.g.,
    - [OII]$\lambda\lambda$3726,3727 , [SII]$\lambda\lambda$6717,6731
    - Limited sensitivity to large dynamic range in density

Hot Gas

- Gas heated to 10^6 K (probably by SNe)
  - Powerful probe of mass distribution in galaxy clusters
- Detected via X-ray emission
  - Point source population
  - Diffuse hot gas
- Emission via
  - Brehmstrahlung
  - Emission lines of highly ionized species

Diffuse Hot Gas: Soft X-Ray Background

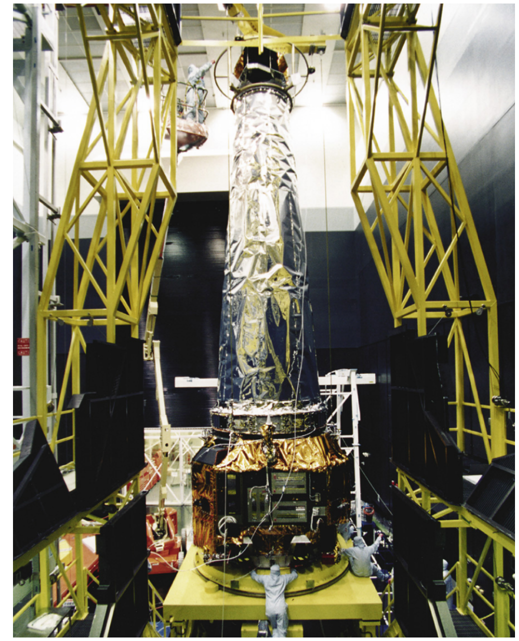
- McKee & Ostriker (1977): diffuse hot phase of the ISM with a filling factor of ~100%
- Early detection of X-ray emitting "superbubbles" in the Milky Way: Sco-Cen, Orion-Eridanus (McCammon et al. '83, McCammon & Sanders '90)
- Origin of Soft X-Ray background
  - MWG: local ISM + hot galactic halo
  - Local Group: hot intergalactic medium
  - Extragalactic: (un)resolved AGN + E galaxies

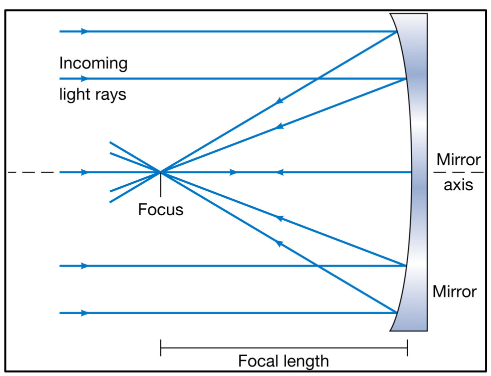
The Local Bubble

- Radius: 100-200 pc
- Temperature: ~2 x 10^6 K
- Thermal pressure: p/k = 10^4 cm^{-3} K
- N(HI) = 6 x 10^{18} cm^{-2} (derived from soft X-ray absorption)
- Origin of the Local Bubble
  - hot gas w/ 100% filling factor?
  - diffuse gas reheated by recent SNe?
  - a series of 2-5 SNe a few million years ago?
  - an extension of nearby superbubble?

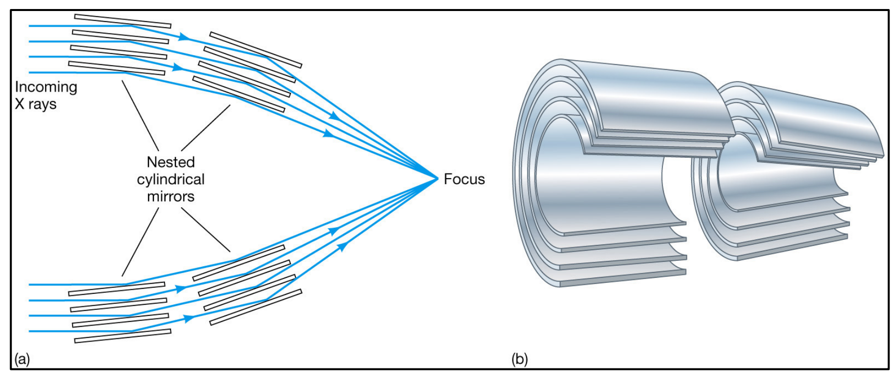
Comparison of X-Ray Observatories

- Einstein: 1' resolution
  - M101 (McCammon & Sanders 1984)
  - L_X(diffuse) ~ 10^{38}-10^{40} erg s^{-1}
- ROSAT (PSPC): 1.'8 resolution, 0.1-2 keV
  - M101, N3184, N4395, N5055, N4736 (Cui et al. 1996)
- CXO (Chandra): <1" over 8 arcminutes
- XMM/Newton: 15" over 30 arcminutes

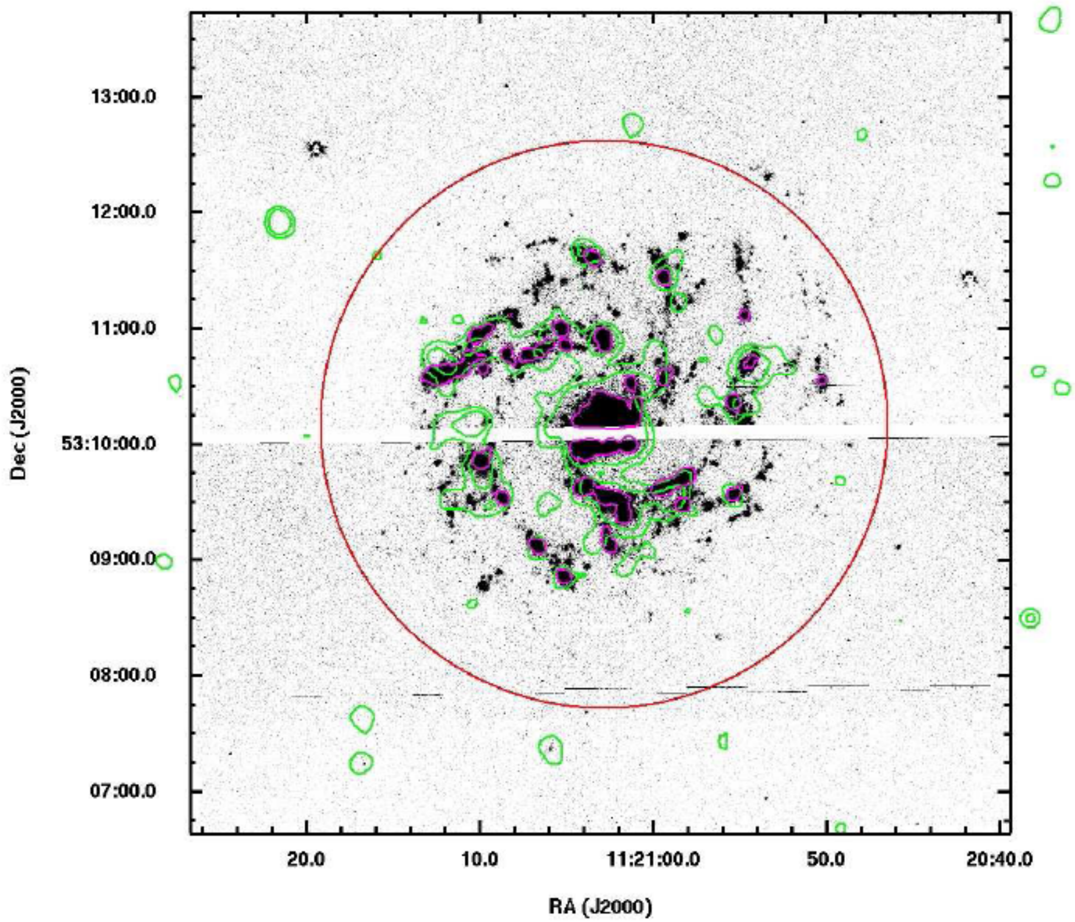




Mirrors:
←Optical
X-ray→



X-ray vs HII region comparison NGC 3631



X-ray emission

Hα emission (WIYN)

(Doane et al. 2007)

Temperature Comparison (10^6K)

- LMC Superbubbles: 1.7-9
- Orion-Eri.: 3.3
- N. P. Spur: 3.0
- Sco-Cen: 4.6

- NGC3631: 1, 3
- NGC6946: 2, 7
- M101: 2 ,8
- N253(halo): 4
- M82(halo): 3, 4

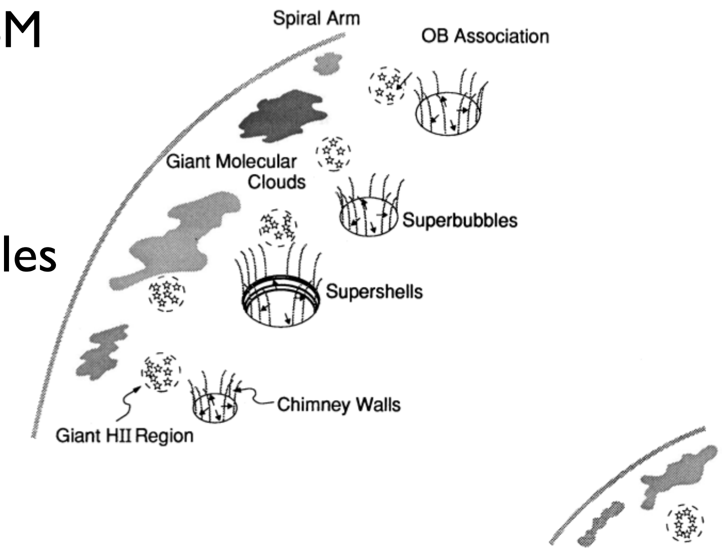
Spirals are best fit with two temperature models of hot gas, but there is variation in the high temperature and surface brightness.

Summary of X-Ray Results

- Diffuse emission is highly correlated with both spiral arms and HII regions
- Bulk of the diffuse emission arises from less than 25% of the area of the disk
- X-ray spectra are best fit with a two temperature model
- There is variation in the surface brightnesses between galaxies and variation in the temperature of the hot component

Feedback: Impact of Massive Stars

- Stellar winds + SNe dump $10^{53.5}$ ergs into ISM
- Creates hot bubble surrounded by swept up ISM and circumstellar matter
  - gas heated by inward moving shock
- X-ray emission should be aligned with HI holes
- growth of chimneys
  - means of getting hot gas into the halo



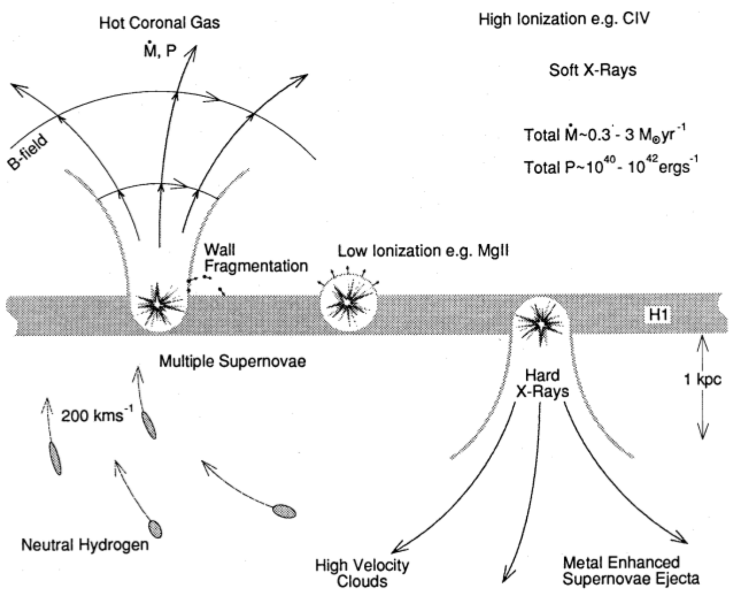
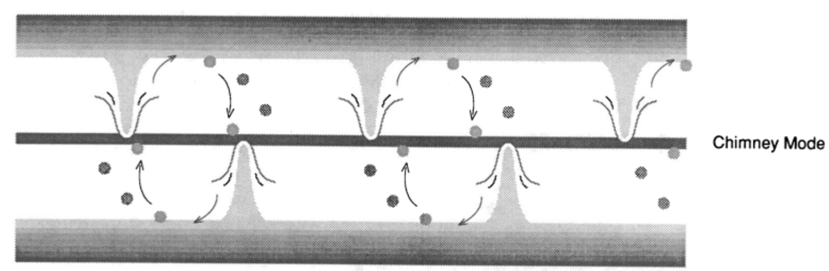


FIG. 4a



Norman & Ikeuchi 1989

Feedback: Bubbles

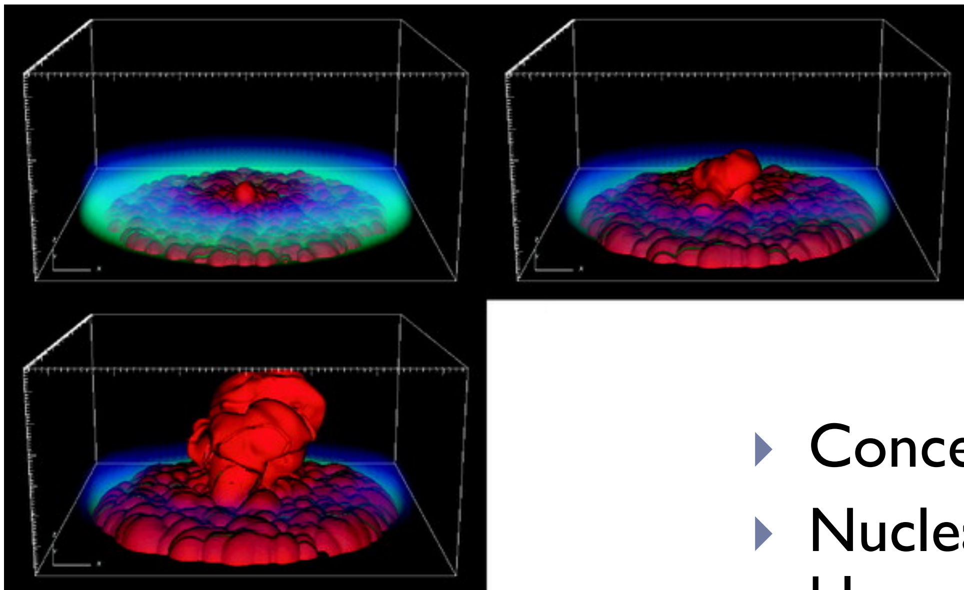
- Stellar winds/SNe drive expanding bubbles into ISM
  - $R_s \sim 100\ (N_* E_{51}/n_0)^{1/5} t_7^{3/5}$ pc (McCray & Kafatos 1987)
  - $V_s = L_W^{1/5} n_0^{-1/5} t_7^{-2/5} \sim 6\ (N_* E_{51}/n_0)^{1/5} t_7^{3/5}$ km s^{-1}
  - Reverse shock heats bubble to 10^6-10^7 K → X-ray emitting
  - Shell includes swept up ISM, dense neutral gas, possibly accelerated particles

R_s – shell size
N_* - number of stars formed with $M>7M_\odot$
T_7 – time-scale in 10^7 yr
E_{51} - SN energy / 10^{51} ergs
n_0 – intial electron density cm^{-3}
V_s – shell speed
L_W – mechanical luminosity of winds

- Ultimate fate
  - Shell/bubble expands until $P_{bubble} = P_{ISM+IGM}$
  - Breaks out of disk if

    $P_{bubble} > P_{ambient}$, $V_{shell} > V_{escape}$
  - Shell accelerates in density gradient

Extreme "Feedback"



- Concentrated SNe
- Nuclear starburst → complete blowout of the ISM
  - What will M82 look like in 10^7-10^9 years?
  - Bursting dwarfs?