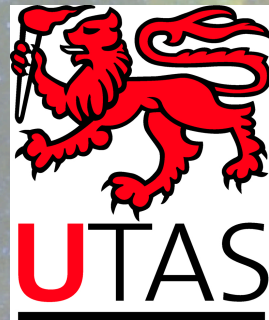


Spectral Line Observations: Enter a New Dimension

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Other sources

- “Tools of Radio Astronomy” Rohlfs & Wilson (Springer).
- Andrew Walsh’s (JCU) spectral line talk at ATNF 2009 Radio School.
- Dirk Muder’s (MPIfR) talk at ESSEA.
- NRAO Astro534 course
- Haystack undergraduate lab on NH_3 obs.
- 37 google searches

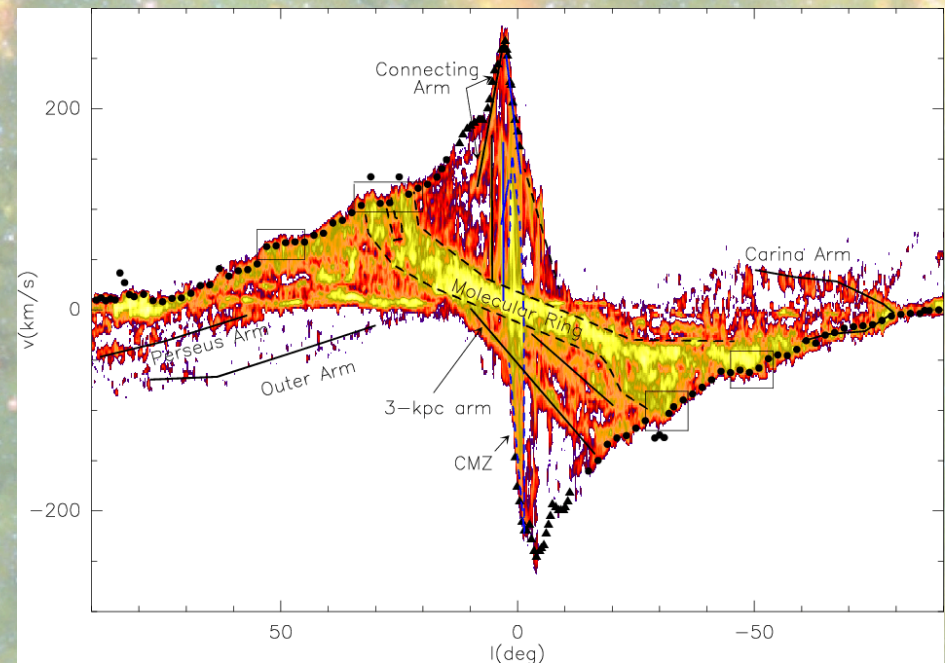
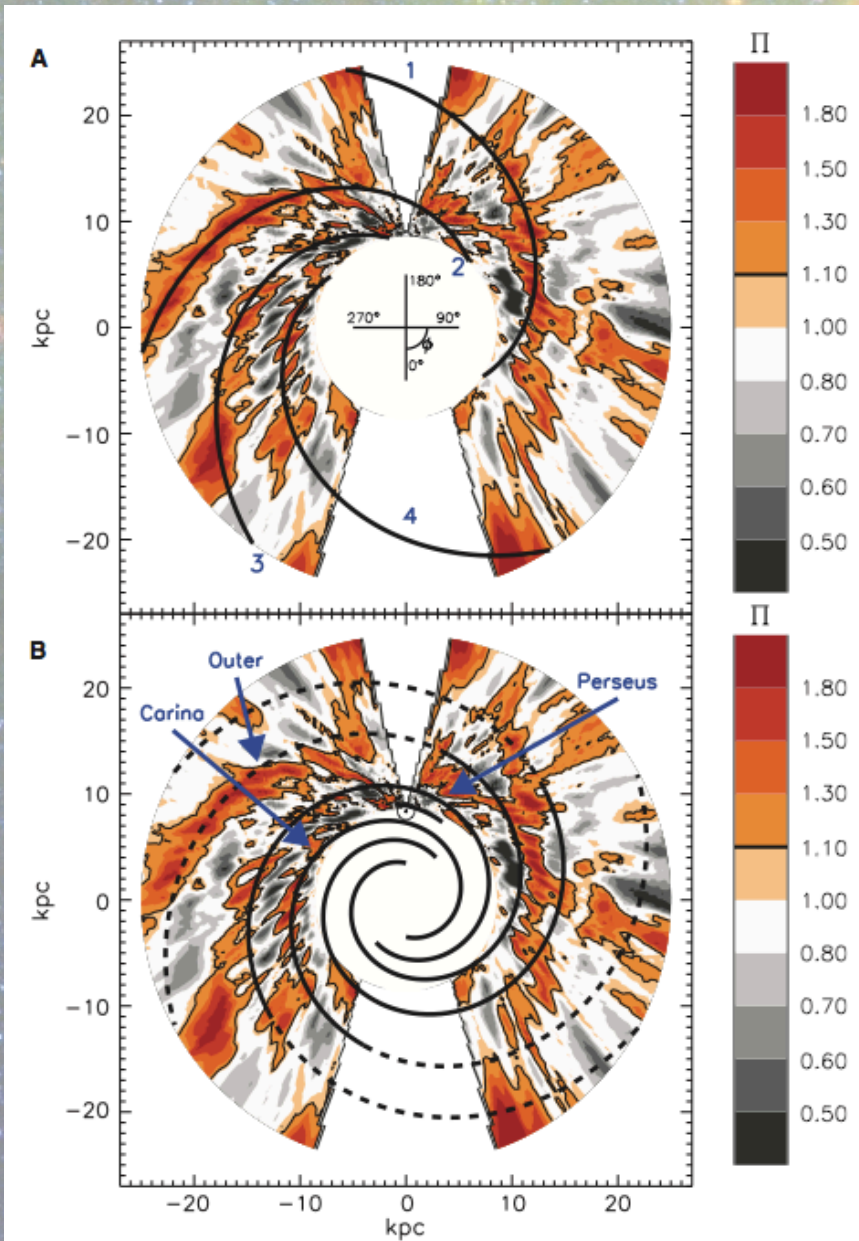


Outline

- Spectral lines, for 3D Astronomers.
- Know your Spectrometer!
- Observing spectral lines.
- Spectral line production mechanisms.
- Science with spectral lines.
- Traps for young (and old) players.

Spectral Lines – Astronomy in 3D

- Astronomical images take a 3D Universe and project it into 2D.
- When we observe a spectral line we measure both its intensity, and the line-of-sight component of velocity
- The structure of our Galaxy has largely been studied through atomic (HI) and molecular (CO) emission and absorption.



Left : Galactic structure modeled from HI overdensity (Levine et al. 2006, Sci. 312, 1776).

Above : CO(1-0) longitude-velocity diagram (Dame et al. 2001, ApJ, 547, 792)

Know your Spectrometer

- If you are planning spectral line observations there are a few basic things you need to determine:
 1. The total velocity coverage.
 2. The optimal velocity resolution.
 3. The correct sky frequency for the observations.
 4. The expected intensity of the line.

Velocity Coverage

- For radio/millimetre frequency observations $\frac{\Delta f}{f} \approx \frac{\Delta v}{c}$

where Δf is the bandwidth (Hz), f the rest frequency (Hz), Δv the velocity span (kms^{-1}) and $c = 3 \times 10^5 \text{ kms}^{-1}$, the speed of light.

- So if you want a velocity coverage of 100 kms^{-1} at a frequency of 22.2 GHz then

$$\Delta f = \frac{100}{3 \times 10^5} \times 22.2 \times 10^9 = 7.4 \text{ MHz}$$

- Allow some leeway for filter edge effects.

Velocity Resolution

- It is good practice to have a velocity resolution with at least 3 spectral channels between the half-power points of a typical spectral line.
- So if you have lines with typical FWHM of 1 kms^{-1} at 22.2 GHz then you want a spectral resolution of

$$\Delta f = \frac{1/3}{3 \times 10^5} \times 22.2 \times 10^9 = 25 \text{ kHz}$$

- Many correlators have a maximum channel-bandwidth product. Often you want to select the configuration with maximum bandwidth for the required velocity resolution.



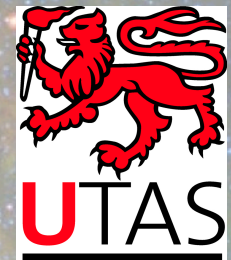
The Art of Compromise

Imagine you want to observe a large sample of Galactic water masers (22.235 GHz).

- Typical FWHM $0.5 - 1.0 \text{ kms}^{-1}$ (vel. res. $\sim 12 \text{ kHz}$).
- Milky Way systemic velocities range $\pm 120 \text{ kms}^{-1}$, masers offset up to 100 kms^{-1} . (velocity coverage $\sim 32 \text{ MHz}$)

At Parkes the multibeam correlator with mbcc_32_8192 or DFB3 with sdfb3_64_8192 would work well.

While at the ATCA a 64 MHz zoom mode is a good choice (or alternatively stitched 16 MHz zooms).



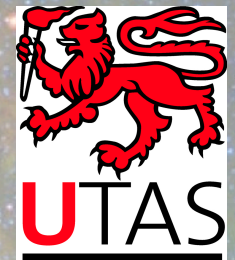


From Monty Python "The Meaning of Life"

<http://www.youtube.com/watch?v=JWVshkVF0SY>

Spectral Line Observations: CASS Radio

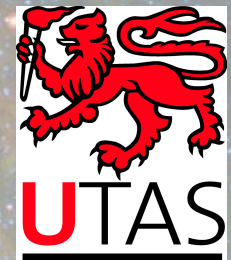
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The Correct Sky Frequency

- The component of the observatory's motion towards the target source is continuously changing.
- The diurnal component is relatively small : $< 0.5 \text{ kms}^{-1}$
- The annual component is important : $< \sim 30 \text{ kms}^{-1}$
- Knowing both the reference frame and the velocity convention is critical.
- The link below takes all the hard work out of getting it right.

<http://www.narrabri.atnf.csiro.au/observing/obstools/velo.html>



Sensitivity

- For spectral line observations bigger, really does mean better (the exceptions are very rare).

$$\Delta S = \frac{SEFD}{k\sqrt{\beta\tau}}$$

ΔS Predicted RMS in spectral channel (Jy or K)

$SEFD$ = System Equivalent Flux Density (Jy) or T_{sys} (K)

β = Bandwidth of spectral channel (Hz)

τ = Integration time (s)

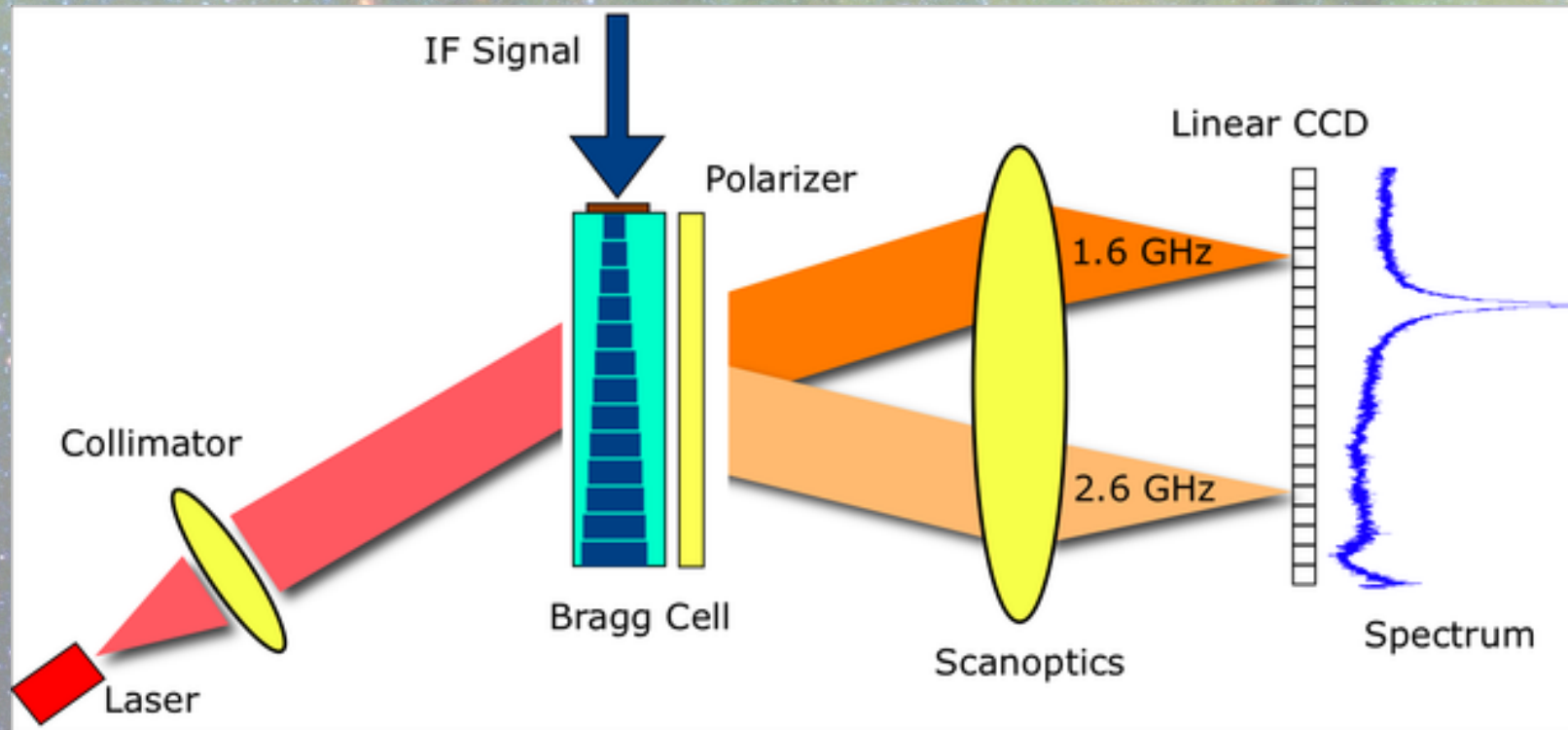
$k = 2/\pi = 0.64$ (1 bit) ; 0.87 (2 bit) ; $\rightarrow 1$ (more bits)

- Observing speed approximately $\propto \text{Area}^2$

Spectrometers

- At radio frequencies we can't use lenses and gratings to form a spectrum.
- Common types of spectrometers include :
 - Digital autocorrelation spectrometers.
 - Acousto-optical spectrometers (used to be common at mm observatories).
 - Filter banks (digital or analogue).
- These each have different strengths and weaknesses.

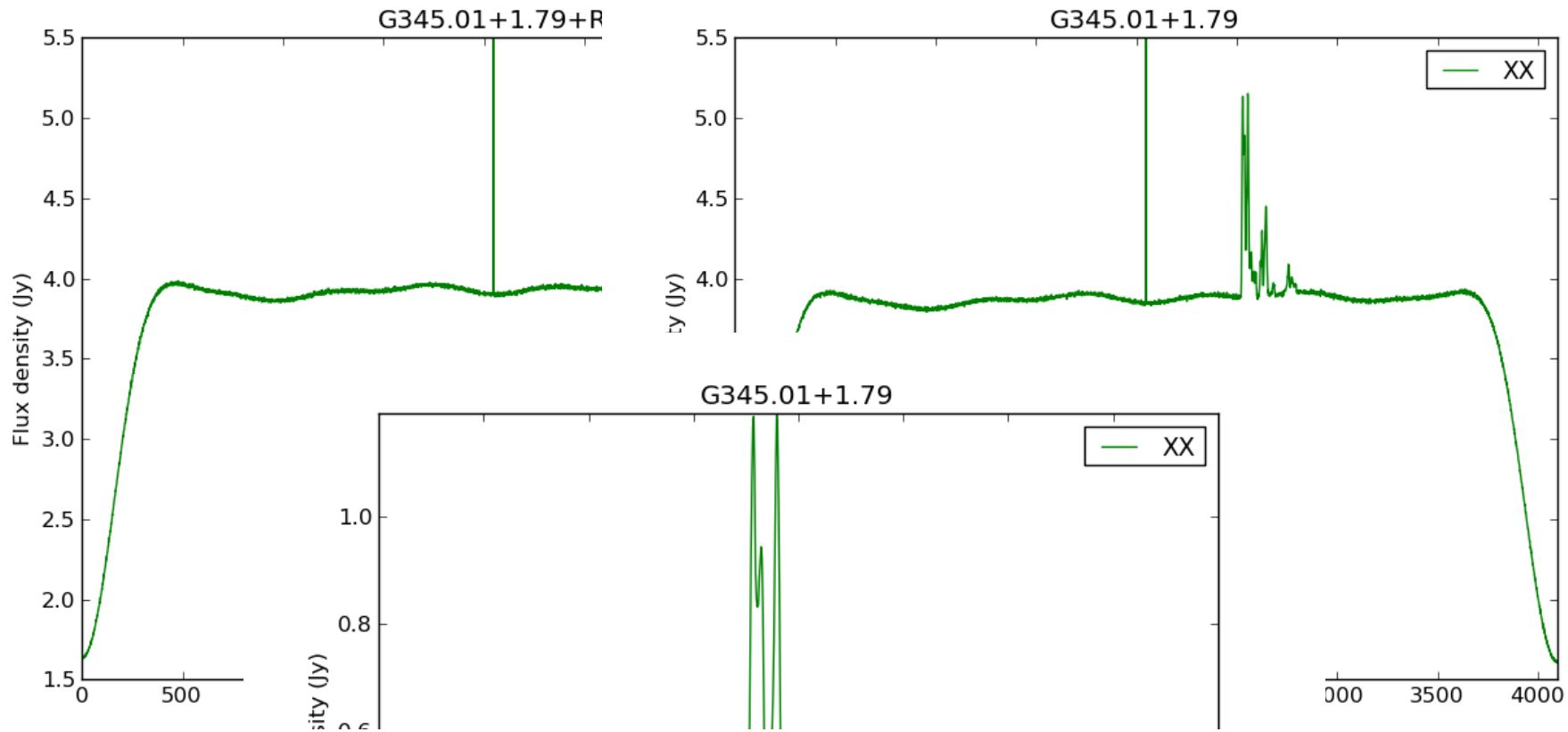
An AOS



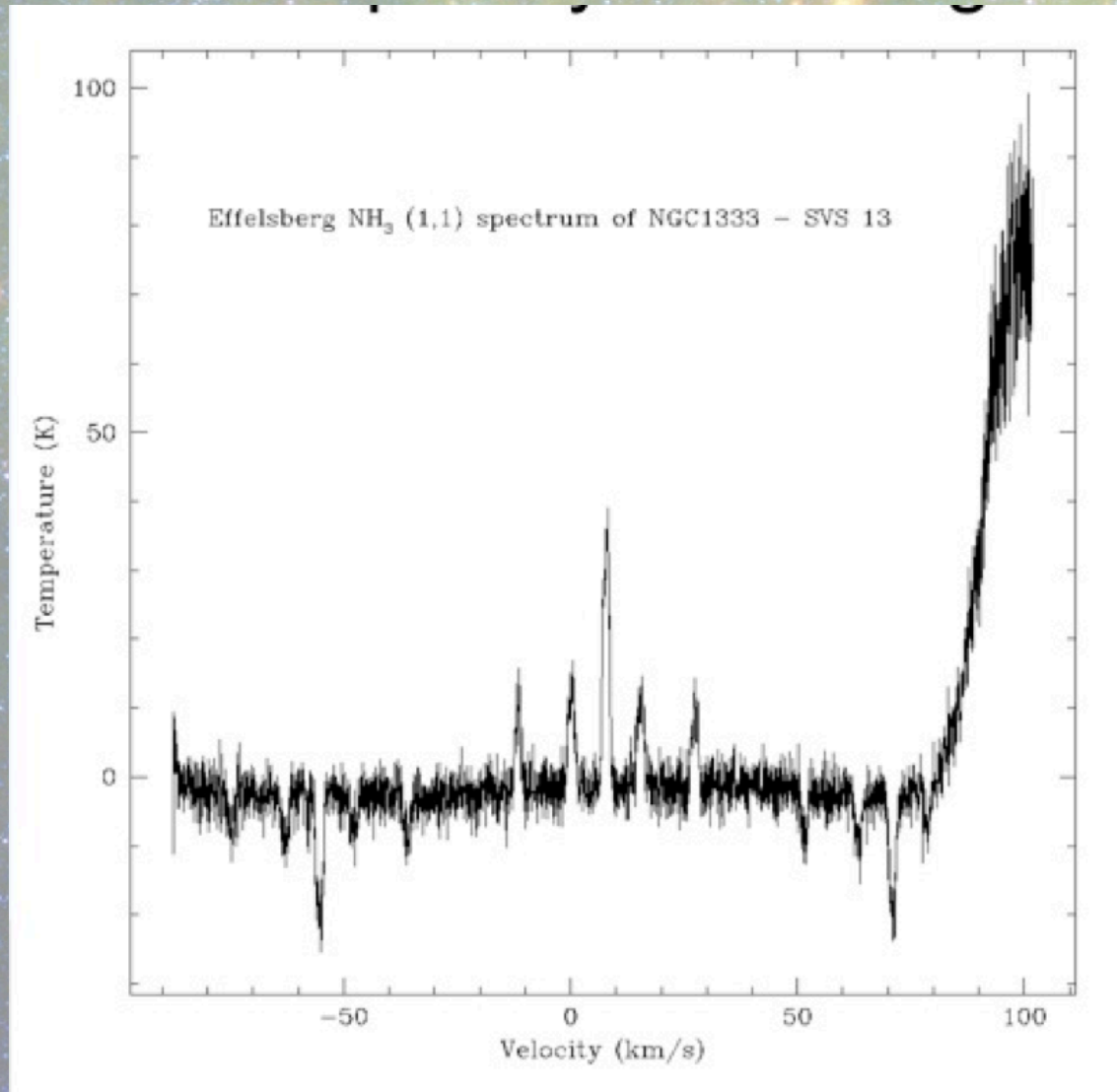
http://en.wikipedia.org/wiki/Acousto_Optical_Spectrometer

Forming a Spectrum

- The line strengths are typically a small fraction of the system noise and often much smaller than the variations in the bandpass/filter response.
- There are a variety of methods for removing the bandpass response :
 - position switching ;
 - frequency switching ;
 - specialized methods – median window filters, LSFS etc.
- You often have have overheads $> 50\%$ in spectral line observations.



Position switching increases noise level by a factor of $\sqrt{2}$ and more than doubles the observing time.



A frequency switched spectrum of ammonia (1,1) taken with Effelsberg. Courtesy Andrew Walsh.

Frequency switching makes more efficient use of the telescope time, but does give you negative images of the emission.

Alternative methods which are similarly efficient :

Median window filters (implemented in ASAP and used in a number of Parkes projects).

Least squares frequency switching (LSFS) Heiles, 2007, PASP

Ring, Ring

- In an autocorrelation spectrometer spectral lines with width's comparable to the channel bandwidth will cause “ringing”.
- The measured ACF is the convolution of the true ACF and a top-hat function (sinc function response).
- Hanning smoothing largely removes this, at the cost of decreased spectral resolution (2 x channel BW).
- Flux density calibration and correction for atmospheric effects are usually carried out at this stage.

Spectral line Production Mechanisms

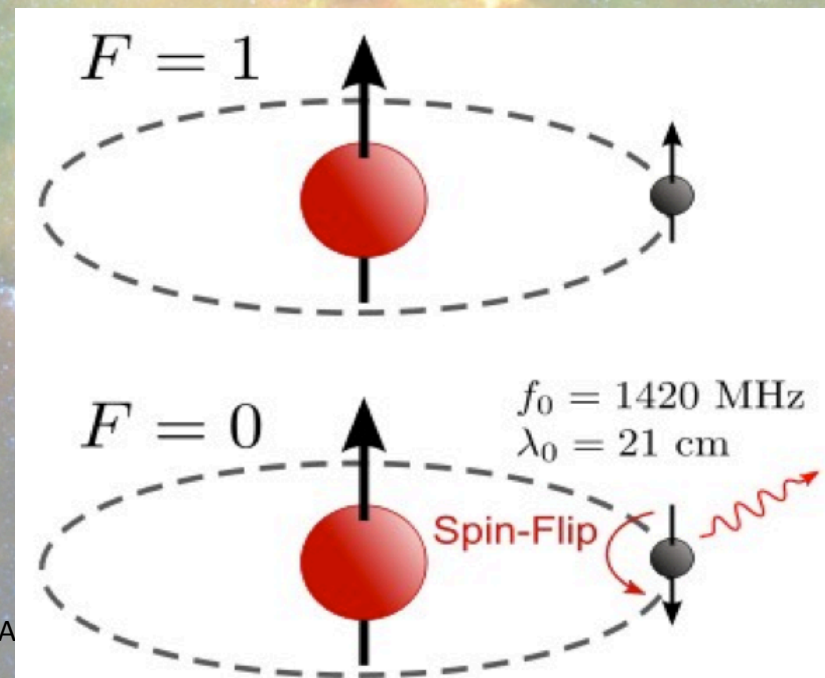
- There is a well-defined energy difference associated between any pair of quantum states.
For example :
 - Electrons changing energy levels in an atom (mainly optical and higher frequencies).
 - Transitions between rotational or vibrational states in molecules (requires electronic dipole moment).
 - Spin-flip transitions (i.e. HI).
- The lines can be seen in emission from warm/hot gas, or in absorption from foreground cool gas with a background continuum source.

Line Spectra

- Although spectral lines occur at well defined energies (frequencies) the lines do have non-zero widths :
 - The uncertainty principle means that the lines have a natural width due to the stochastic nature of spontaneous decay (the natural width).
 - Thermal motion of the gas broadens observed line due to Doppler shifting (observed widths usually significantly exceed the thermal width).
 - Bulk motion due to turbulence, outflows etc. further broadens the lines.
 - In some lines (e.g. H_I, CO), large-scale velocity gradients and absorption along the path complicates further.

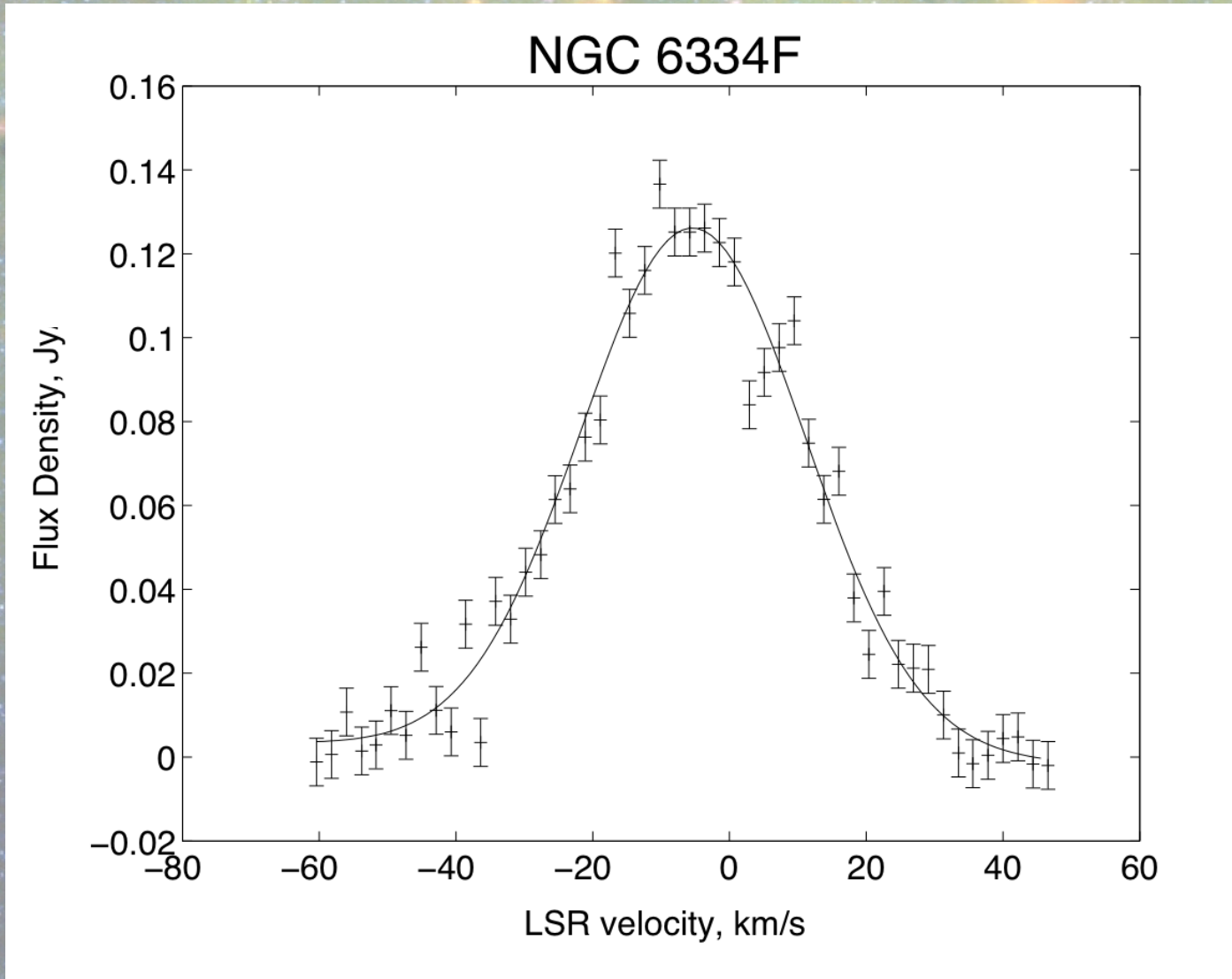
Atomic Hydrogen - HI

- Emission at 21 cm (1420 MHz) is seen when the relative orientation of the proton and electron spins change.
- HI is ubiquitous, which is both a positive and a negative.
 - ✓ In many environments it is the only detectable spectral line.
 - ✓ Disentangling emission and absorption from different regions along the same line of sight is often complex



Recombination Lines

- Photons with energy > 13.6 eV ($\lambda < 912$ Å) ionise ground-state hydrogen.
- When the ionised hydrogen recombines the electron is often in a highly excited (high n) state.
- Overtime the system decays to the ground state through one or more spontaneous transitions to lower n states.
- In addition to hydrogen, recombination lines are also seen from single-electron He and C and can be used to infer atomic abundances.



ATCA observation of the H91 α emission from the HII region NGC6334F (Shabala et al. 2006)

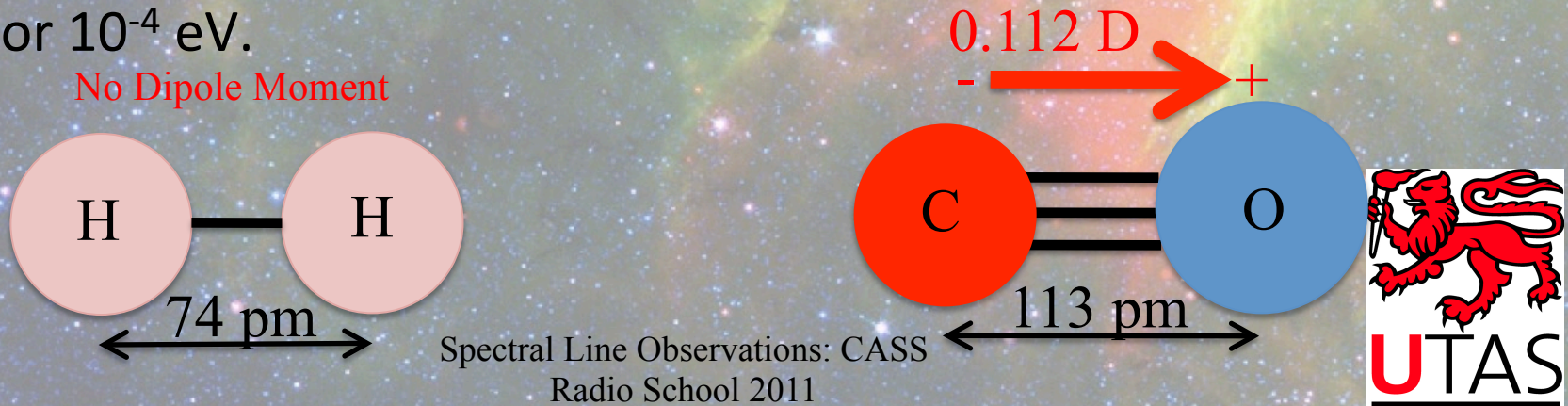


Rotational Spectra

- A simple diatomic molecule can be approximated as two point masses at a fixed separation.
- So the rotational energy of the molecule is $E_r = \frac{\hbar^2}{2I} r(r+1)$
- And adjacent rotational energy levels are separated in energy by

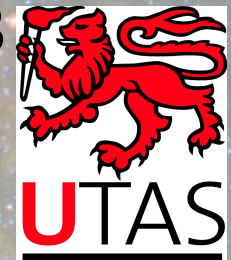
$$\Delta E_r = E_r - E_{r-1} = \frac{\hbar^2}{2I} [r(r+1) - (r-1)r] = \frac{\hbar^2}{I} r$$

- For typical molecules this energy difference is around 10^{-3} or 10^{-4} eV.



The Molecular Zoo

- H_2 is by far the most common molecular gas, but because it is symmetric it is hard to get it to emit spectral lines.
- CO is the Big Mac™ of the molecules – diatomic molecule with abundant elements and low critical density.
- As of August 2011 there have been ~165 different molecules observed in interstellar space (see <http://www.astro.uni-koeln.de/cdms/>)
- The most complex of them (HC_{11}N) containing 13 atoms



More spectral lines

- At radio and millimetre frequencies rotational transitions dominate, while at higher frequencies vibrational transitions are also observed.
- Hyperfine transitions, or isotopomers can allow measurements of optical depth.
- Optically thin molecules can be used to measure the column density of different molecules.
- Optically thick molecules can potentially be used to measure the temperature.

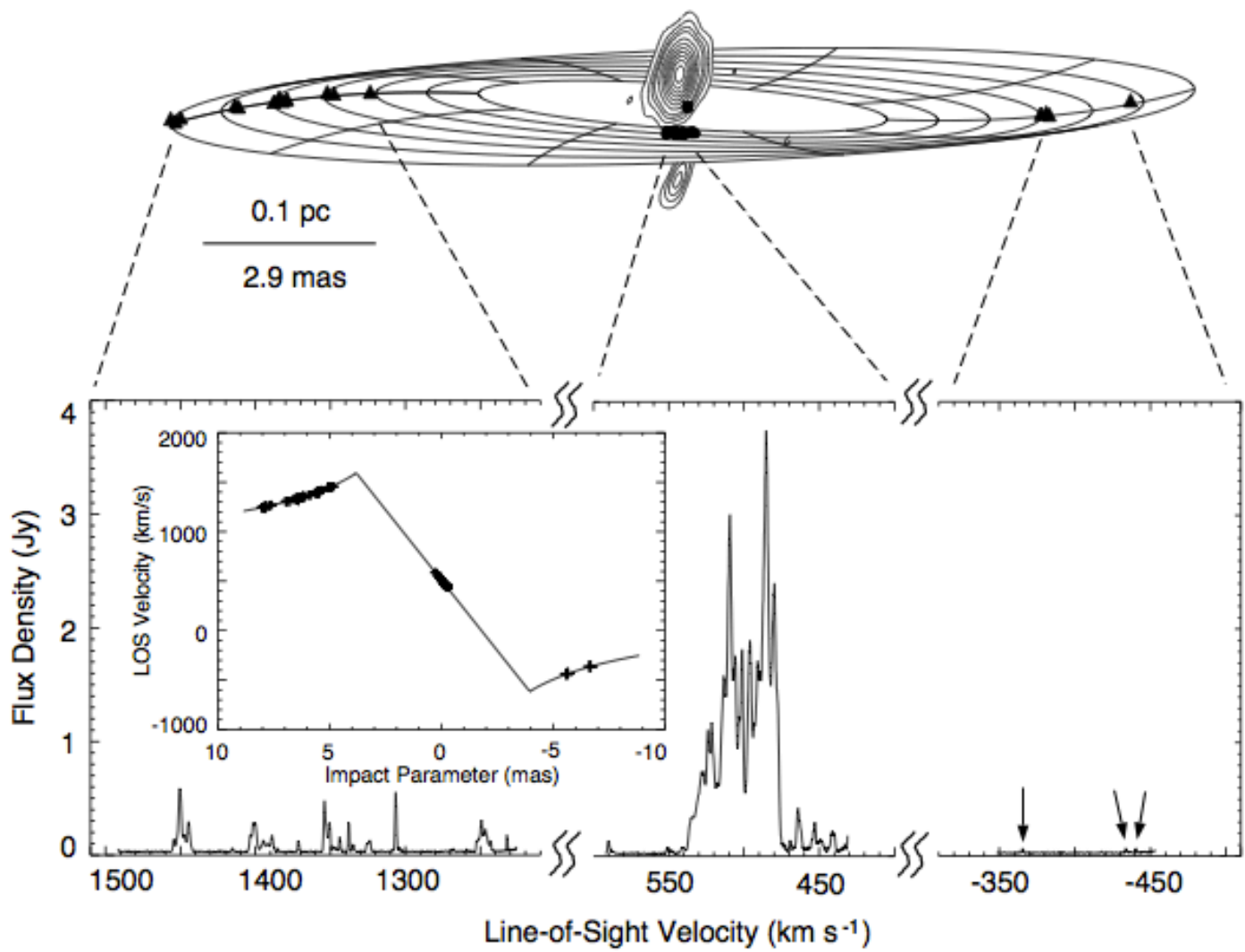
Microwave Amplification by Stimulated Emission of Radiation

- Masers

- Non-LTE conditions are relatively common in interstellar space (low T and ρ mean collisions rare).
- In combination with quantum mechanical selection rules this means that masers can arise naturally.
- Masers from a range of molecules (OH , H_2O , CH_3OH) are commonly observed in a variety of astrophysical environments.
 - Star formation regions.
 - Late-type stars.
 - AGN, SNR, Comets, ...

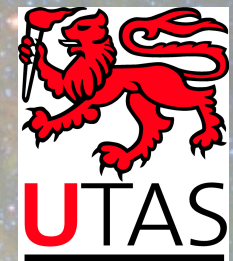
Kinematics

- Spectral lines can tell you about kinematics on scales from a few AU to 10's of kpc.
- They have been a primary tool for determining the kinematics of our Galaxy.
- They can be use to measure galactic rotation curves.
- Investigate tidal flows in interacting galaxies.
- Measure infall, outflow and rotation in star formation regions.
- Trigonometric parallax of masers is transforming our understanding of Galactic kinematics.



The water masers in the Seyfert 2 galaxy NGC4258 provide the best evidence of a supermassive blackhole at the centre of a galaxy (Herrnstein et al. 1999).

Spectral Line Observations: CASS Radio
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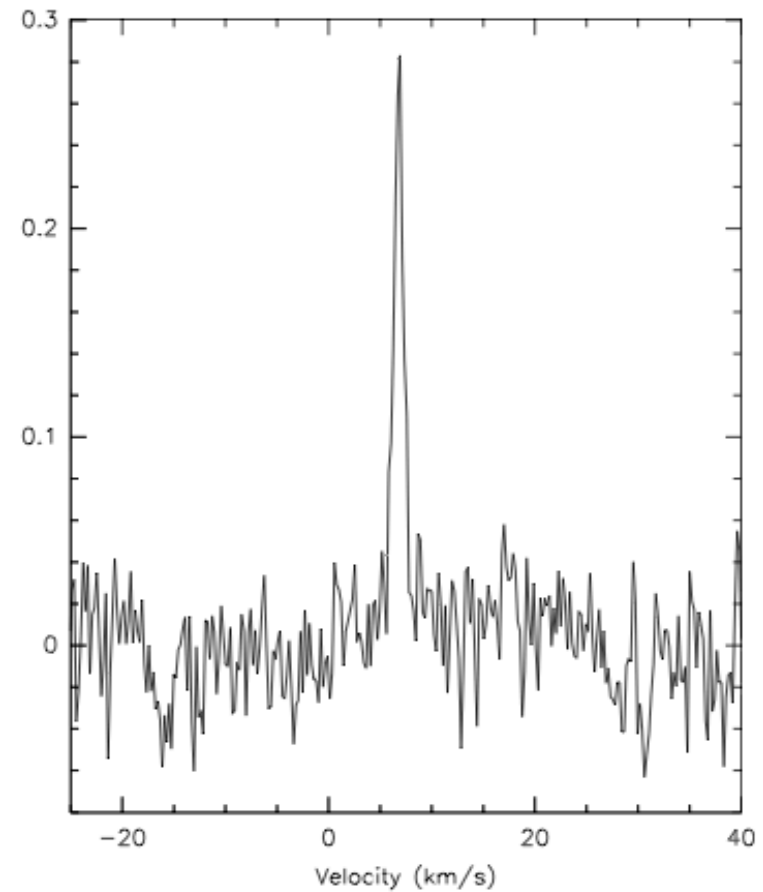
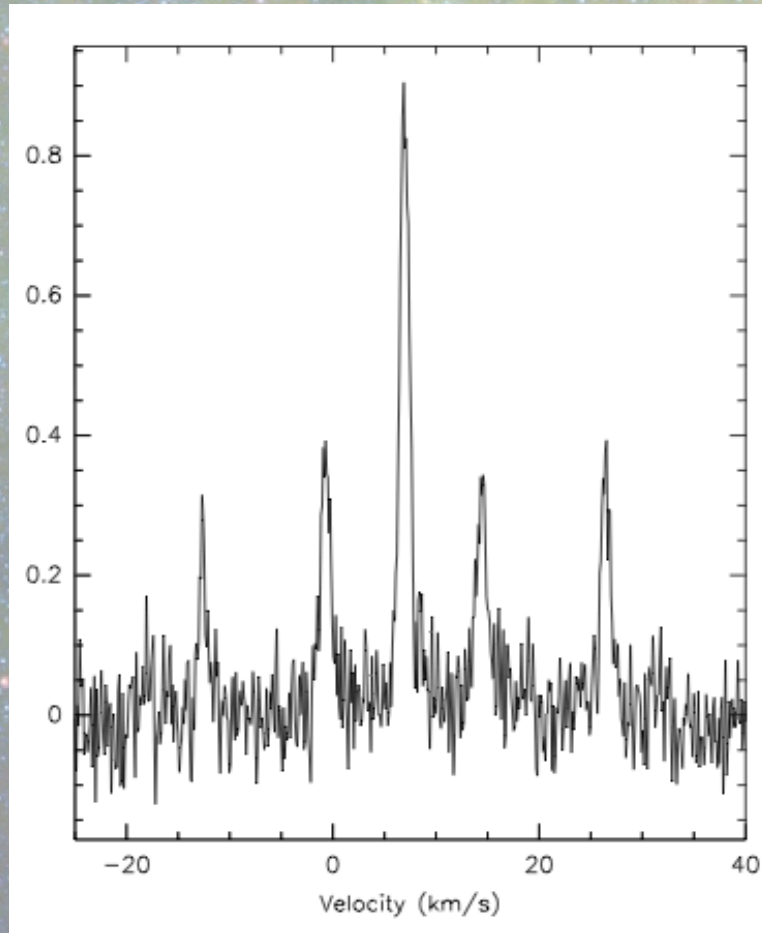


Chemistry

- The presence (and absence) of different molecules traces the chemistry and chemical evolution of a region. For example :
 - Complex molecules form on dust grains in cold, dense molecular clouds.
 - They are released through heating by radiation and/or shocks.
 - Gas-phase reactions, dissociation from radiation and shocks then change the chemical composition.
- Comparing the relative abundance of the different molecules with models can be used to infer ages etc

Physics

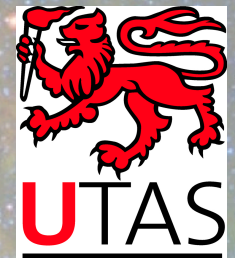
- The differing critical densities of molecules means that their presence/absence can be related to the gas density.
 - CO (1-0) 4000 cm^{-3} ; CO(2-1) 20000 cm^{-3} , CO(4-5) $4.89 \times 10^5 \text{ cm}^{-3}$.
 - CS (2-1) $6.0 \times 10^5 \text{ cm}^{-3}$; HCO⁺(1-0) $1.64 \times 10^5 \text{ cm}^{-3}$; HCN (1-0) $2.2 \times 10^6 \text{ cm}^{-3}$
- Some molecules (e.g. NH₃), can be used to infer the temperature.
 - Measurement of the (1,1) and (2,2) transitions at ~ 23.7 GHz can be used to determine the optical depth, rotation and kinetic temperature.



The spectrum of NH_3 (1,1) - left and (2,2) – right taken with the Haystack 37m telescope towards the Orion molecular cloud. (from www.haystack.mit.edu/edu/undergrad/materials/nh3-lab.pdf)

Traps for Young (and Old) Players

1. Polarization due to edge of bandpass effects.
 - At the edge of the bandpass where it starts to roll-off the relative gain of the channels can change and give apparent polarization.
2. Temporal variations due to line-widths comparable to the channel & poor velocity alignment.
 - The interpolation algorithms used by some software (e.g. miriad, ASAP) to velocity align spectra doesn't work well in this case.



Conclusions

- The techniques and science of spectral line observations are very broad.
- Increasing backend (correlator) power means that most modern radio/millimetre facilities have excellent spectral capabilities.
- For continuum or other observations spectral lines can often give you complementary information.
- Questions?