Spectral Line Observing II

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Spectral Line Observing II. Outline

- Editing and Flagging
- Bandpass Calibration
- Imaging and Deconvolution
- Continuum Subtraction
- Data Visualization and Analysis

Editing and Flagging of Spectral Line Data

Compared with continuum mode observing, the spectral line observer is faced with some additional data editing/flagging/quality assessment challenges:

- much larger data sets

- narrow-band interference (RFI) may be present at certain frequencies

- sidelobes of distant sources (e.g., the Sun) may contaminate short spacings

Editing and Flagging of Spectral Line Data

Initial editing of spectral line data can be performed efficiently using a Channel 0* dataset.

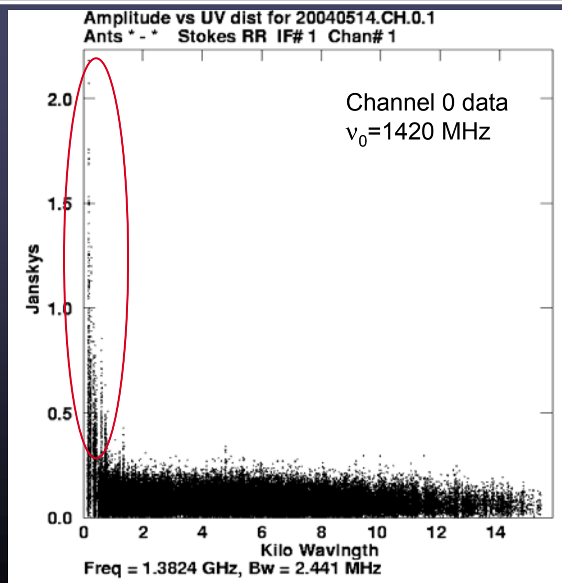
The improved S/N of the Channel 0 data aids in identifying problems affecting all frequency channels (e.g., malfunctioning electronics or mechanical problems with a particular antenna; solar contamination).

Resulting flags are then be copied to the line dataset and applied to *all* spectral channels.

*Channel 0 = a pseudo-continuum data set formed by vector-averaging the inner ~75% of the spectral band.

Example of solar interference contaminating short *u-v* spacings during a daytime VLA observation of a galaxy in the HI 21-cm line

Amplitude

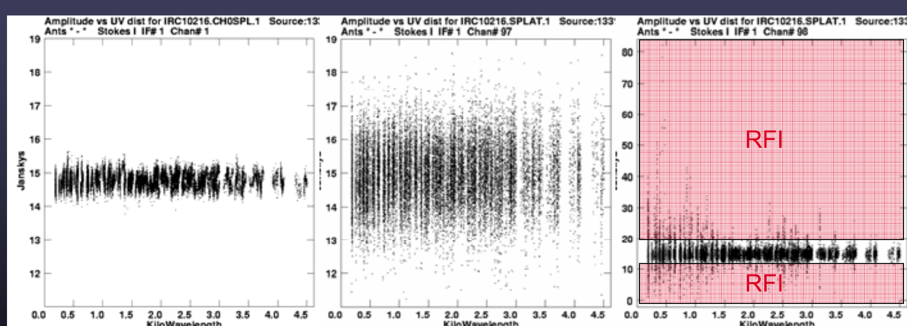


baseline length (*u-v* distance)

Editing and Flagging of Spectral Line Data

Plots of visibility amplitudes versus baseline length for calibrator source 3C286 at 1420MHz:

Channel 0 ($\Delta\nu$=0.58MHz) Channel 95 ($\Delta\nu$=6.1kHz) Channel 98 ($\Delta\nu$=6.1kHz)



Certain frequency-dependent problems (e.g., RFI) may not be obvious in Channel 0 data; always check the line data too!

Editing and Flagging of Spectral Line Data

For large data sets, checking the data channel-by-channel is not practical. This task can be simplified using approaches such as:

- Examination of cross-power spectra: check for dips or spikes

- Use of automated flagging routines: these can flag data based on deviation from expected spectral behavior (e.g., AIPS task UVLIN)

- Monitoring closure errors and other problems during subsequent bandpass calibration

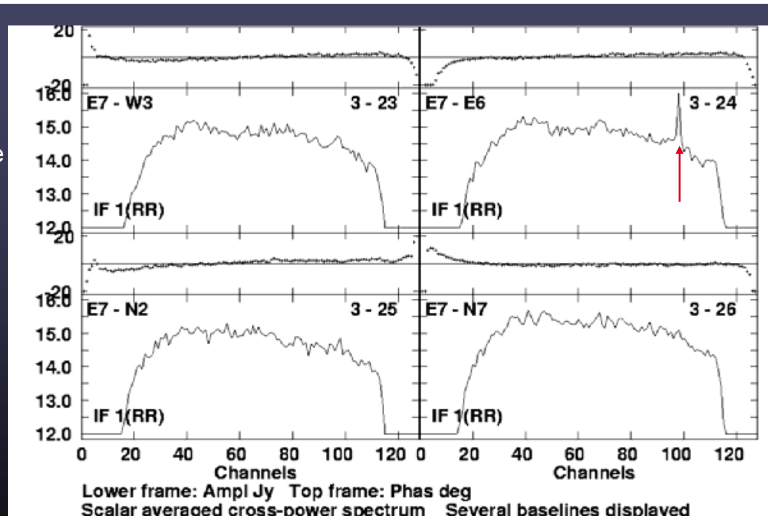
But:

Avoid excessive frequency-dependent flagging: it introduces changes in the *u-v* coverage across the band.

Scalar-averaged cross-power spectra can be helpful for spotting narrowband RFI.

Phase

Amplitude

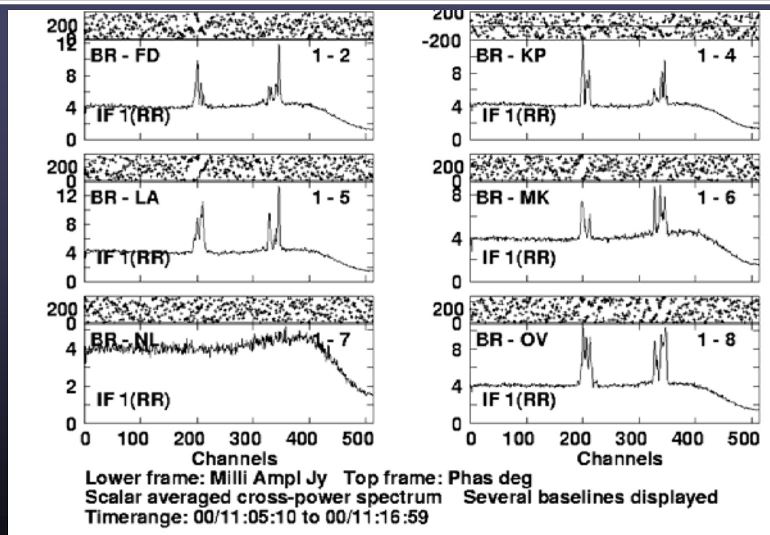


Example: Scalar-averaged cross-power spectra of a calibration source on four different baselines (plots made with AIPS task POSSM).

Scalar-averaged cross-power spectra can reveal on which baselines a signal is detected:

Phase

Amplitude



Example: SiO maser spectra on different VLBA baselines

Bandpass Calibration: What is it?

In general, the goal of calibration is to find the relationship between the observed visibilities, V_{obs}, and the true visibilities, V :

$$V_{i\,j}(t,\nu)_{obs} = V_{i\,j}(t,\nu)G_{i\,j}(t)B_{i\,j}(t,\nu)$$

where t is time, ν is frequency, *i* and *j* refer to a pair of antennas *(i,j)* (i.e., one baseline), *G* is the complex "continuum" gain, and *B* is the complex frequency-dependent gain (the "bandpass").

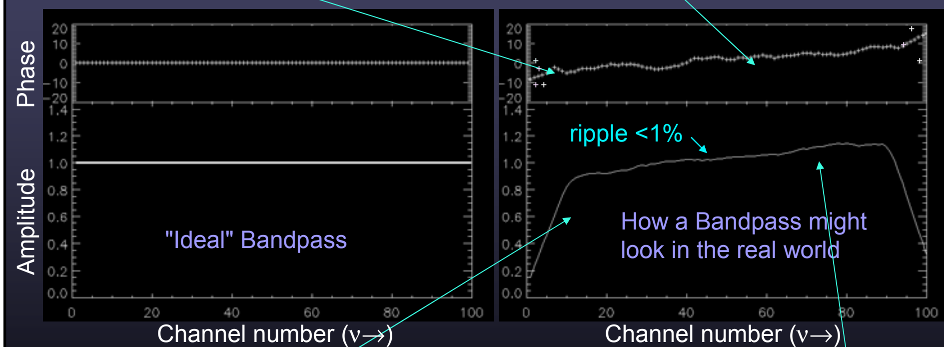
Bandpass calibration is the process of deriving the *frequency-dependent* part of the gains, $B_{i\,j}(t,\nu)$ (i.e., the spectral response function).

$B_{i\,j}$ may be constant over the length of an observation, or it may have a slow time dependence.

What does a typical bandpass look like?

Higher phase noise at band edges caused by ghost sources (Bos 1985; J. Uson 2006)

Phase slope of a few degrees across band from delay errors



Edge roll-off caused by shape of baseband filters

Bandpass calibration attempts to correct for the deviations of the observed bandpass from the "ideal" one.

nearly flat over inner ~75% of band

Explanation of "Ghost Sources"

The convolution of a flat spectrum with some window function W(ω) produces ripples in the sine spectrum (Gibbs phenomenon).

Since the ripple is absent from the cosine term, the complex visibility has an imaginary error term $\Delta V(\underline{x},\omega)$.

The Fourier transform of this error term produces a "hidden" image, on top of the real image, and a "ghost" source diametrically opposite (about the phase center).

These two sources contribute sidelobes of W(ω) at positive and negative frequencies⇒phase noise in edge channels.

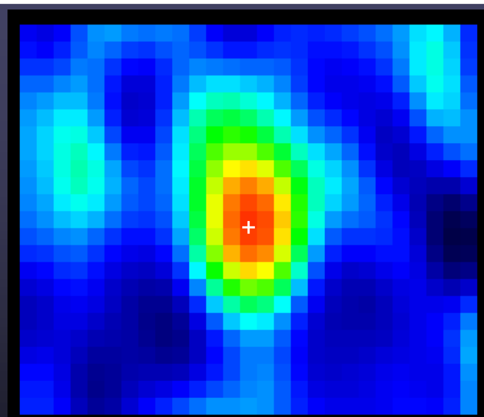
For more information see Bos (1985).

Bandpass Calibration: Why is it important?

The quality of the bandpass calibration is a key limiting factor in the ability to detect and analyze spectral features.

- Bandpass amplitude errors may mimic changes in line structure with ν
- ν-dependent phase errors may lead to spurious positional offsets of spectral features as a function of frequency, mimicking doppler motions of the emitting/absorbing material.
- ν-dependent amplitude errors limit ability to detect/measure weak line emission superposed on a continuum source (simply subtracting off the continuum does not fully alleviate this problem).
- For continuum experiments performed in spectral line mode, dynamic range of final images is limited by quality of bandpass calibration.

Phase errors can lead to shifts in the apparent position (and morphology) of a source from channel to channel:



<u>Rule of thumb:</u>
Relative positional accuracy in channel images: $\Delta\theta / \theta_B = \Delta\phi / 360$
where θ_B is the synthesized beam and $\Delta\phi$ is the scatter in the phases.

Bandpass Calibration: Some Guidelines

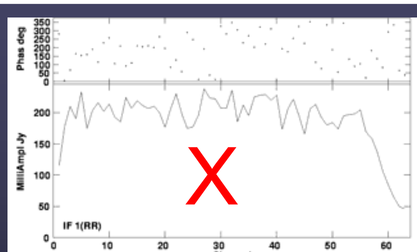
At the VLA, bandpass calibration is typically performed using observations of a strong continuum source.

Within the frequency range of interest, bandpass calibration source(s) should have:
(1) high S/N in each spectral channel
(2) an intrinsically flat spectrum
(3) no spectral features
(4) no changes in structure across the band

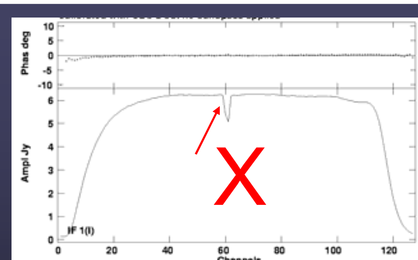
Rule of thumb:
BP calibrator should have sufficient S/N *per channel* so as not to degrade the target spectrum by more than ~10%; i.e.,

$(S/N)_{BP} > 2 \times (S/N)_{target}$

Bandpass Calibration: Some Guidelines

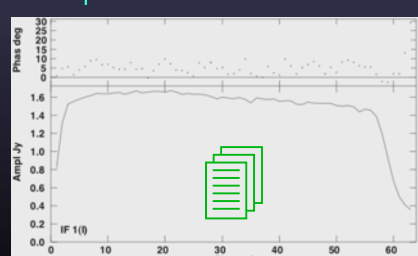


Signal-to-noise per channel too low.



Absorption feature from Galactic HI.

Cross-power spectra of three potential bandpass calibrators.



Good S/N; no spectral features

Computing the Bandpass Calibration

In theory, the frequency spectrum of the visibilities of a flat-spectrum calibration source should yield a direct estimate of the bandpass for each baseline : $B_{ij}(t,\nu) = B_{ij}(t,\nu)_{obs} / S_{cal}$
BUT: this requires very high S/N.

Most corruption of the bandpass occurs before correlation, and is linked to individual antennas.

$\Rightarrow$ *solve for antenna-based gains*: $B_{ij}(t,\nu) \approx B_i(t,\nu)\, B_j(t,\nu)^*$
$= b_i(t,\nu) b_j(t,\nu) \exp[i\, (\phi_i(t,\nu)\phi_j(t,\nu))]$

- Given N antennas, now only N complex gains to solve for compared with $N(N - 1)/2$ for a baseline-based solution.
  - $\Rightarrow$ less computationally intensive
  - $\Rightarrow$ improvement in S/N of ~ sqrt[(N-1) /2]
- Calibration can be obtained for all antennas, even if some baselines are missing.

Computing the Bandpass Calibration

The method commonly used for solving for the bandpass calibration is analogous to channel-by-channel *self-calibration*:

- Calibrator data are either divided by a source model or Channel 0 (this effectively removes any source structure and any uncalibrated continuum gain changes).
- Antenna-based gains are solved for as free parameters.

Note: This approach may require modification if S/N per channel is low, no strong calibrators are available, etc.

Bandpass Calibration: Modified Approaches May Be Required in Some Circumstances

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Signal-to-noise too low to fit channel-by-channel?⇒ try polynomial fit across the band (e.g., AIPS task CPASS).

For VLBI, compact continuum sources strong enough to detect with high S/N on all baselines are rare. ⇒ use autocorrelation spectra to calibrate the amplitude part of the bandpass.

At mm wavelengths, strong continuum sources are rare. ⇒ use artificial noise source to calibrate the bandpass.

Line emission present toward all suitable BP calibrators? ⇒ use a modest frequency offset during the BP calibrator observations.

Ripple across the band? ⇒ smooth the solution in frequency (but note: you then should also smooth the target data, as smoothing will affect the shape of real ripples, and the slope of the bandpass edges)

(For additional discussion see SIRA II, Ch. 12; AIPS Cookbook §4.7.3.)

Assessing the Quality of the Bandpass Calibration

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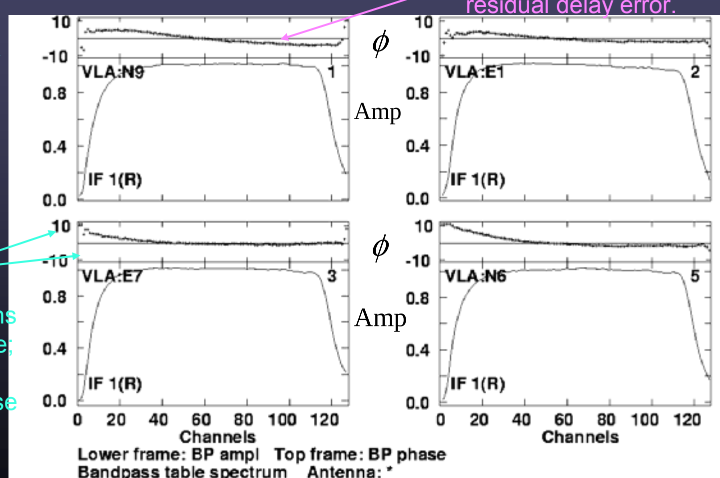
Solutions look comparable for all antennas

Phase slope across band indicates residual delay error.

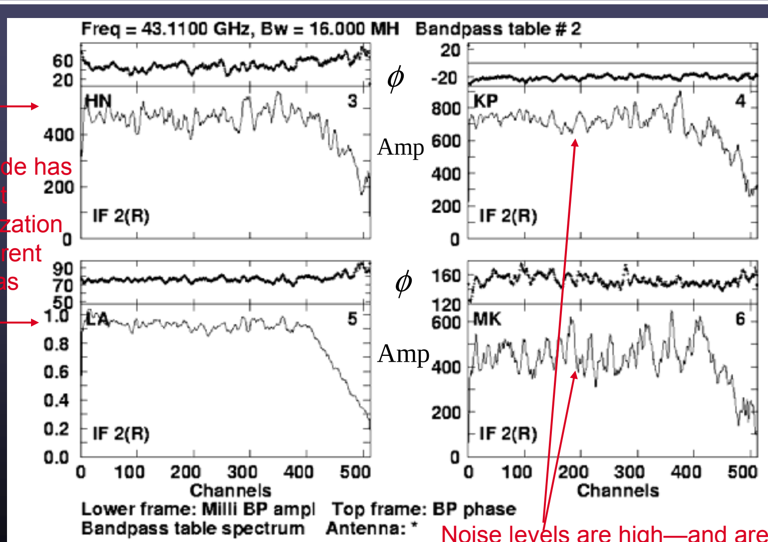
Mean amplitude ~1 across the usable portion of the band

No sharp variations in amp. and phase; variations are not dominated by noise



Examples of good-quality Bandpass solutions for 4 antennas

Assessing the Quality of the Bandpass Calibration

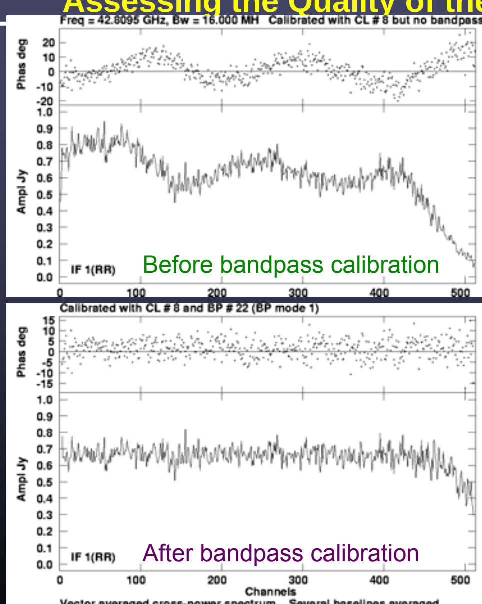


Amplitude has different normalization for different antennas

Noise levels are high—and are different for different antennas

Examples of poor-quality Bandpass solutions for 4 antennas

Assessing the Quality of the Bandpass Calibration



One way to evaluate the success of the BP calibration is by examining cross-power spectra though a continuum source with BP corrections applied.

Checklist:

- ✓Phases are flat across the band
- ✓Amplitude is constant across the band (for continuum source)
- ✓Corrected data do not have significantly increased noise
- ✓Absolute flux level is not biased high or low

Computing the Bandpass Calibration: Closure Errors

Note: If $B_{i\,j}(t,\nu)$ is not strictly factorable into antenna-based gains, then *closure errors* (baseline-based errors) will result.

Closure errors can be a useful diagnostic of many types of problems in the data (e.g., a malfunctioning correlator; a calibration source too weak to be detected on all baselines; RFI).

Imaging and Deconvolution of Spectral Line Data

Deconvolution **("cleaning") is a key aspect of most spectral line experiments:**

- It removes sidelobes from bright sources that would otherwise dominate the noise and obscure faint emission
- Extended emission (even if weak) has complex, often egregious sidelobes
- Total flux cannot be measured from a dirty image.

Remember : interferometers cannot measure flux at "zero spacings":

$$V(u,v)=\iint B(x,y)\, exp(-2\pi\, i(ux + vy))dx\, dy$$

$$(u=0,v=0) \rightarrow Integrated\ flux = \int\int\ B(x,y)\ \ dx\ dy$$

However, deconvolution provides a means to interpolate or "fill in" the missing spatial information using information from existing baselines.

Imaging and Deconvolution of Spectral Line Data

Deconvolution of spectral line data often poses special challenges:

•Cleaning many channels is computationally expensive

• Emission *distribution* changes from channel to channel

• Emission *structure* changes from channel to channel

• One is often interested in *both* high sensitivity (to detect faint emission) and high spatial/spectral resolution (to study kinematics)

Imaging and Deconvolution of Spectral Line Data: A Few Guidelines

Should I vary my cleaning strategy from channel to channel?

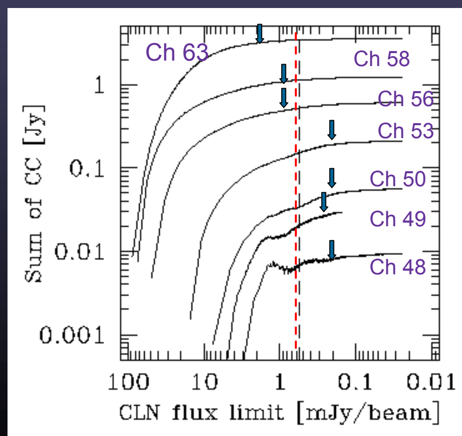
It is generally best to use the same restoring beam for all channels, and to clean all channels to the same depth.

However, it may be necessary to modify any "clean boxes" from channel to channel if the spatial distribution of emission changes.

Imaging and Deconvolution of Spectral Line Data: A Few Guidelines

How deeply should I clean?

Rule of thumb: until the sidelobes lie below the level of the thermal noise or until the total flux in the clean components levels off.

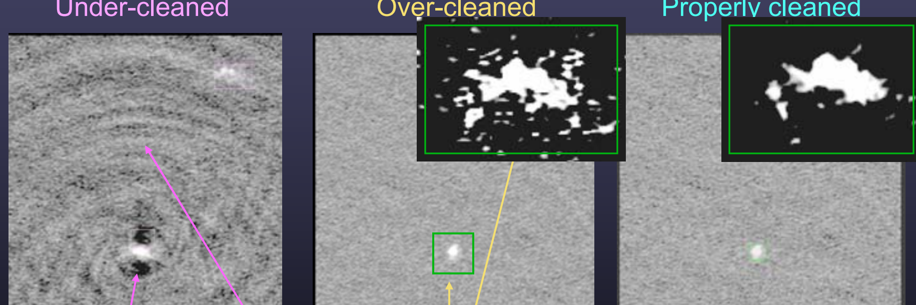


Imaging and Deconvolution of Spectral Line Data: Some Common Cleaning Mistakes

Under-cleaned

Over-cleaned

Properly cleaned



Residual sidelobes dominate the noise

Emission from second source sits atop a negative "bowl"

Regions within clean boxes appear "mottled"

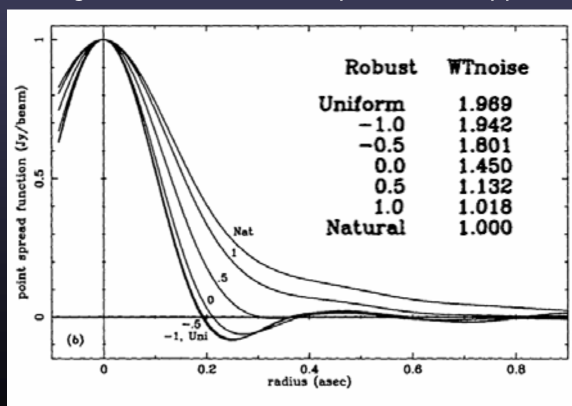
Background is thermal noise-dominated; no "bowls" around sources.

Imaging and Deconvolution of Spectral Line Data: A Few Guidelines

What type of weighting should I use?

Robust weighting (with $\mathcal{R}$ between -1 and 1) allows the production of images with a good compromise between spatial resolution, sensitivity to extended emission, and low rms noise.

⇒ *a good choice for most spectral line applications.*



Uniform weighting ≈ $\mathcal{R}$=–5

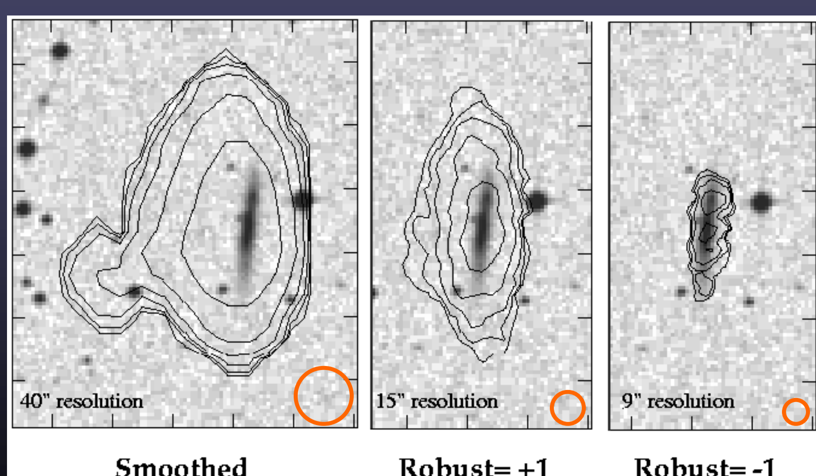
Natural weighting ≈ $\mathcal{R}$= 5

from Briggs et al. (1999) (SIRA II, p. 136)

Imaging and Deconvolution of Spectral Line Data: A Few Guidelines

What type of weighting should I use?

from J. Hibbard



HI contours overlaid on optical images of an edge-on galaxy

Some Notes on Smoothing Spectral Line Data

Spatially:
Smoothing data spatially (through convolution in the image plane or tapering in the *u-v* domain) can help to emphasize faint, extended emission.

Caveats:

This only works for *extended* emission.

This cannot recover emission on spatial scales larger than the largest angular scale to which the interferometer is sensitive.

Smoothing effectively downweights the longer baselines, leaving fewer data points in the resulting image; this tempers gains in S/N.

Some Notes on Smoothing Spectral Line Data

In frequency:
Smoothing in frequency can improve S/N in a line if the smoothing kernel matches the line width ("matched filter").

Caveats:
In general, channel width, spectral resolution, and noise equivalent bandwidth are all different: $\Delta\nu_c \neq \Delta\nu_R \neq \Delta\nu_N$

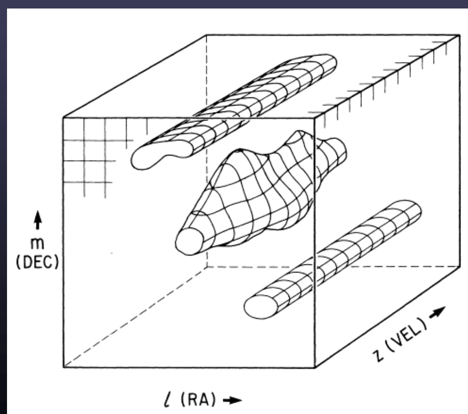
$\Rightarrow$ Smoothing in frequency does not propagate noise in a simple way.

Example: data are Hanning smoothed to diminish Gibbs ringing
- Spectral resolution will be reduced from $1.2\Delta\nu$ to $2.0\Delta\nu$
- Noise equivalent bandwidth is now $2.67\Delta\nu$
- Adjacent channels become correlated: ~16% between channels i and i+1; ~4% between channels i and i+2.

$\Rightarrow$*further smoothing or averaging in frequency does not lower noise by sqrt(*n_{chan}*)*

Continuum Subtraction

Spectral line data frequently contain *continuum emission* (frequency-independent emission) within the observing band:
- continuum from the target itself
- neighboring sources (or their sidelobes) within the telescope field of view



Schematic of a data cube containing line+continuum emission from a source near the field center, plus two additional continuum sources.

from Roelfsema (1989)

Continuum Subtraction

Continuum emission and its sidelobes complicate the detection and analysis of the spectral line features:

- weak line signals may be difficult to disentangle from a complex continuum background; complicates measurements of the line signal

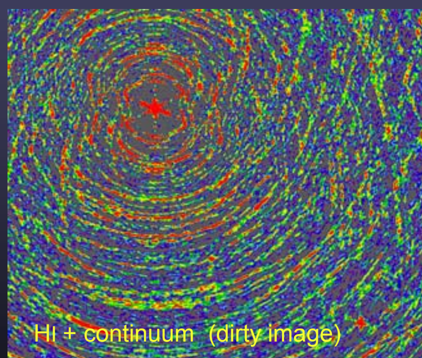
- multiplicative errors scale with the peak continuum emission
  $\Rightarrow$*limits the achievable spectral dynamic range*

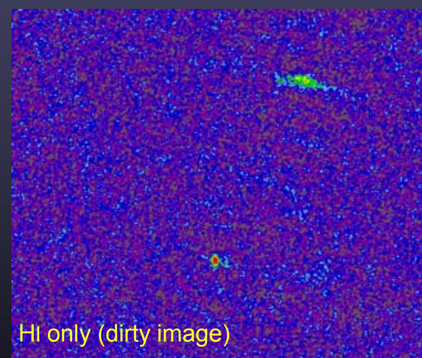
- deconvolution is a non-linear process; results often improved if one does not have to deconvolve continuum and line emission simultaneously

- if continuum sources are far from the phase center, will need to image large field of view/multiple fields to properly deconvolve their sidelobes

Dirty images of a field containing HI line emission from two galaxies, before and after continuum subtraction.

30"





Peak continuum emission in field: ~1 Jy; peak line emission: ~13 mJy

Continuum Subtraction: Approaches

Subtraction of the continuum is frequently desirable in spectral line experiments.

The process of continuum subtraction is *iterative*: examine the data; assess which channels appear to be line-free; use line-free channels to estimate the continuum level; subtract the continuum; evaluate the results.

Continuum subtraction may be:
- visibility-based
- image-based
- a combination of the two

No one single subtraction method is appropriate for all experiments.

Continuum Subtraction: Visibility-Based

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Basic idea: (e.g., AIPS tasks UVLIN, UVBAS, UVLSF)
1. Fit a low order polynomial to a select group of channels in the *u-v* domain.
2. Subtract the fit result from all channels.

Pros:
- Fast and easy
- Robust to common systematic errors
- Accounts for any spectral index across the band
- Can automatically output continuum model
- Automatic flagging of bad data possible

Cons:
- Channels used in fit must be *entirely* line-free
- Requires line-free channels on both ends of the band
- Noise in fitted channels will be biased low in your images
- Works well only over a restricted field of view: $\theta << \nu_0 \, \theta_s / \Delta\nu_{tot}$ (see Cornwell, Uson, and Haddad 1992)

Continuum Subtraction: Clean Image Domain

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Basic approach: (e.g., AIPS task IMLIN)
1. Fit low-order polynomial to the line-free portion of the data cube
2. Subtract the fit from the data; output new cube

Pros:
- Fast
- Accounts for any spectral index across the band
- Somewhat better than UVLIN at removing continuum away from phase center (see Cornwell, Uson, and Haddad 1992)
- Can be used with few or no line-free channels (if emission is localized and/or blanked prior to fitting)

Cons:
- Requires line and continuum to be simultaneously deconvolved; $\Rightarrow$ good bandpass+deep cleaning required (but very effective for weak/residual continuum subtraction)

Continuum Subtraction: Visibility+Image-Based

Basic idea: (e.g., AIPS task UVSUB)

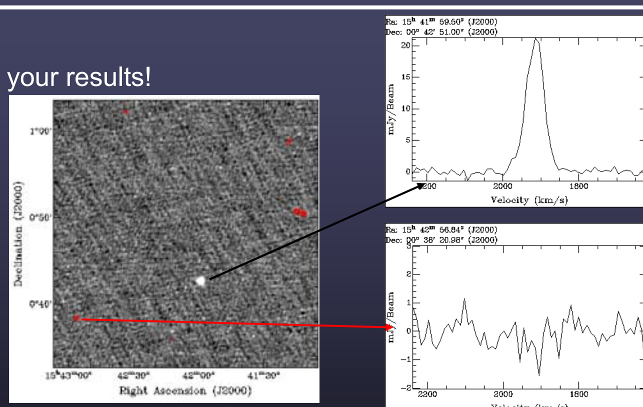
1. Deconvolve the line-free channels to make a "model" of the continuum
2. Subtract the Fourier transform of the model from the visibility data

Pros:
- Can remove continuum over a large field of view

Cons:
- Computationally expensive
- Any errors in the model (e.g., deconvolution errors) will introduce systematic errors in the line data

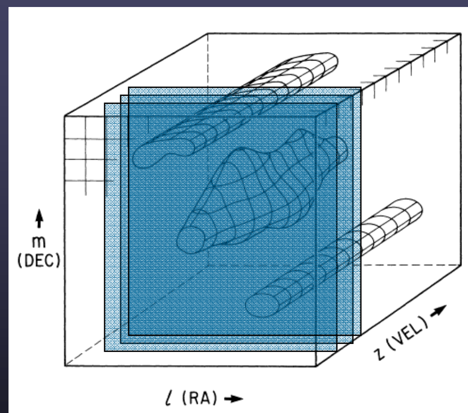
Continuum Subtraction: Additional Notes

• Check your results!

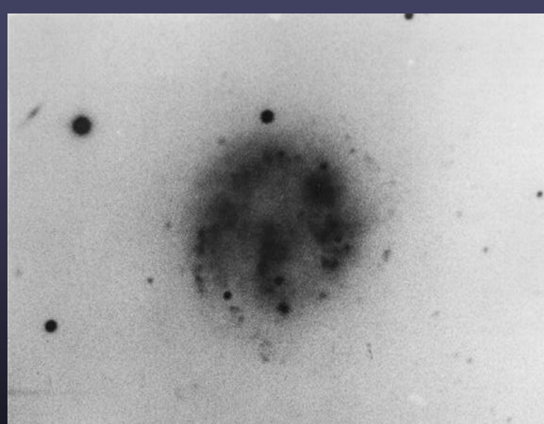


• Always perform bandpass calibration before subtracting continuum.

Visualizing Spectral Line Data

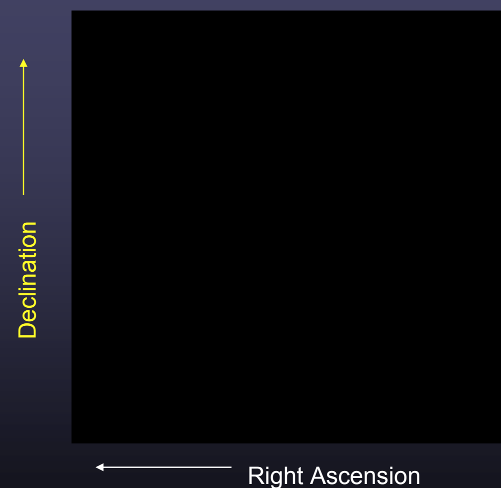


After editing, calibrating, and deconvolving, we are left with an inherently 3-D data set comprising a series of 2-D spatial images of each of our frequency (velocity) channels.



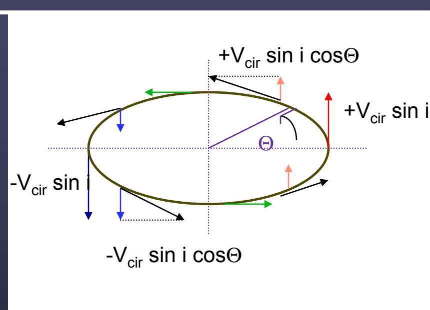
Optical image of peculiar face-on galaxy from Arp (1966)

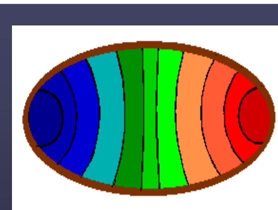
Visualizing Spectral Line Data: Movies



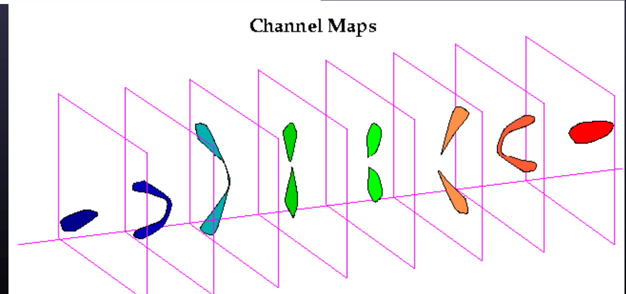
"Movie" showing a consecutive series of channel images from a data cube.
This cube contains HI line emission from a rotating disk galaxy.

Schematic Data Cube for a Rotating Galaxy Disk





Mean Velocity Field



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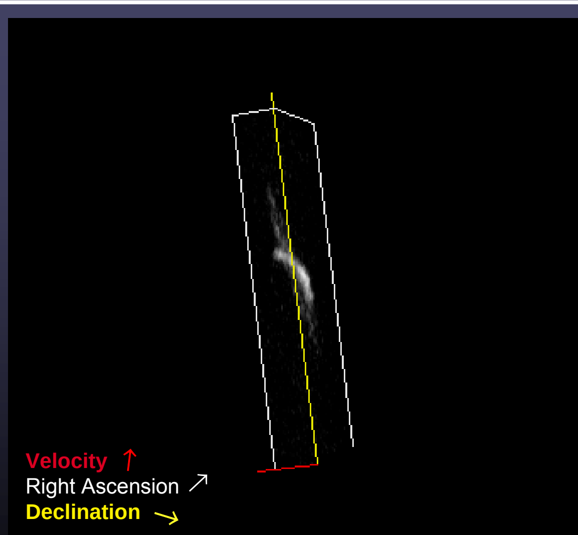
Visualizing Spectral Line Data: 3-D Rendering



Display produced using the 'xray' program in the karma software package (http://www.atnf.csiro.au/software/karma/)

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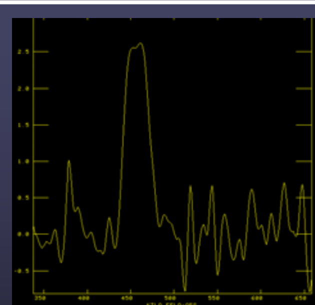
Visualizing Spectral Line Data: Conveying 3-D Data in Two Dimensions

The information content of 3-D data cubes can be conveyed using a variety of 1-D or 2-D displays:

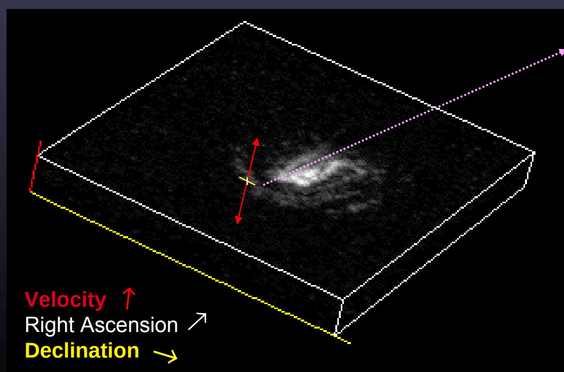
- 1-D slice along velocity axis = line profile
- Series of line profiles along one spatial axis = position-velocity plot
- 2-D slice at one point on velocity axis = channel image
- 2-D slices integrated along the velocity axis = moment maps

Visualizing Spectral Line Data: Line Profiles

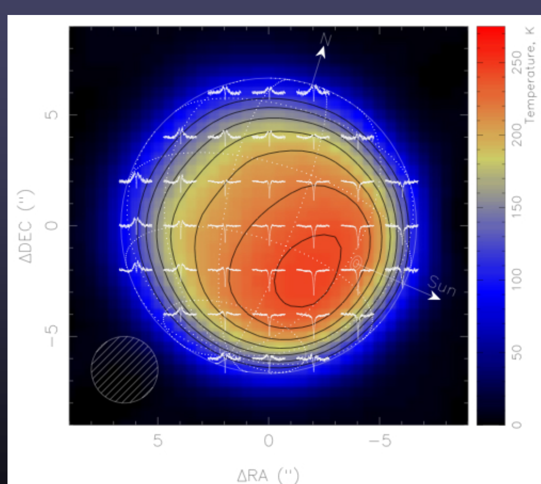
Flux density



Velocity



Visualizing Spectral Line Data: Line Profiles



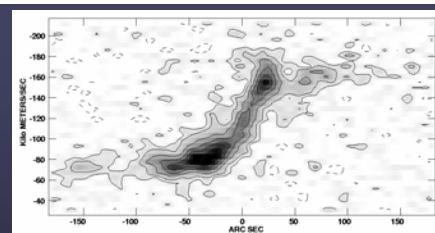
SMA CO(2-1) line profiles across the disk of Mars, overplotted on 1.3mm continuum image.

Credit: M. Gurwell (see Ho et al. 2004)

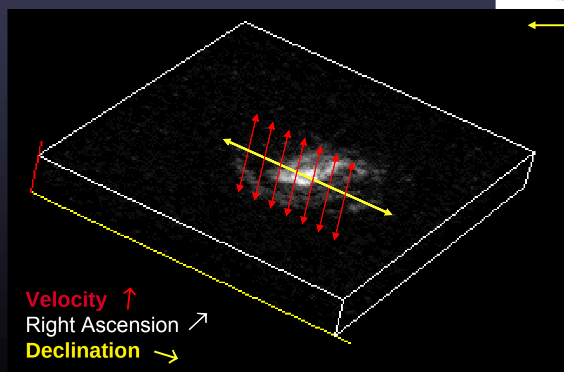
Changes in line shape, width, and depth probe the physical conditions of the Martian atmosphere.

Visualizing Spectral Line Data: Position-Velocity Plots

Velocity profile

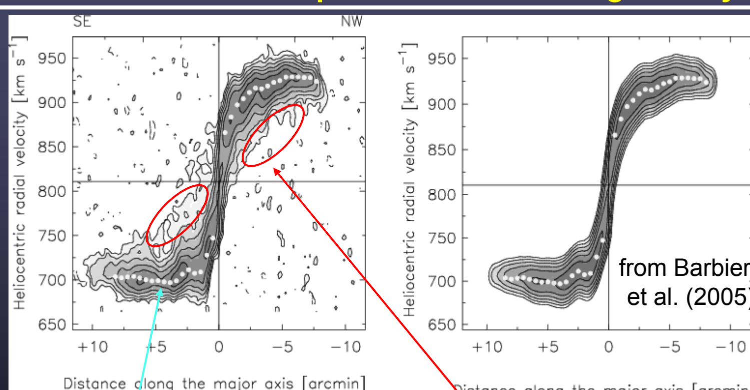


Distance along slice



Greyscale & contours convey intensity of the emission.

Sample Application of P-V Plots: Identifying Anomalous Gas Component in a Rotating Galaxy

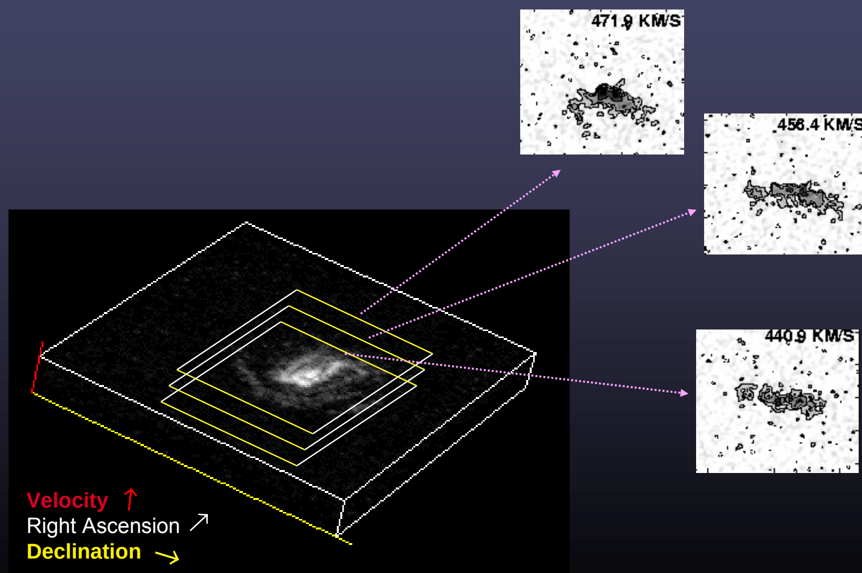


Fitting of line profiles along a P-V curve can yield the **rotation curve** of a galaxy disk (white dots).

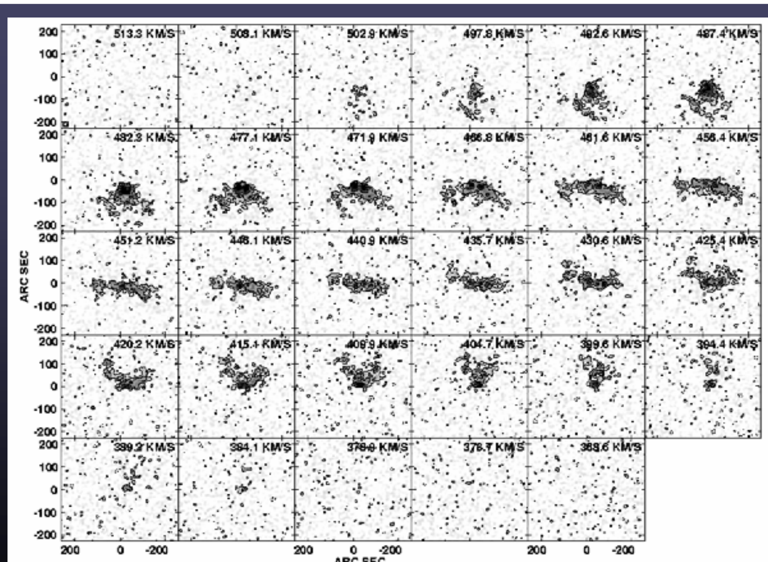
Comparison of model to observed P-V diagram reveals gas at unexpected velocities⇒rotationally lagging HI "thick disk"

Models computed using GIPSY (www.astro.rug.nl/~gipsy.html)

Visualizing Spectral Line Data: Channel Images

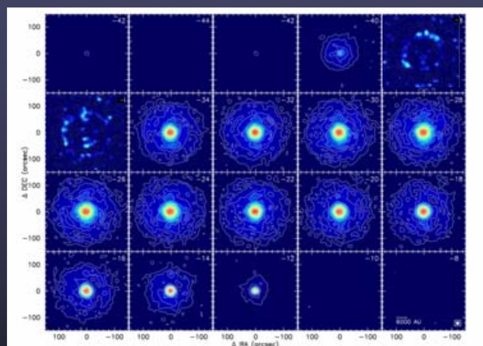


Visualizing Spectral Line Data: Channel Images



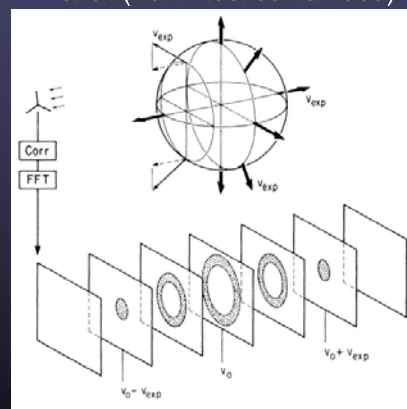
Greyscale+contour representations of individual channel images

Sample Application of Channel Map Analysis: An Expanding Circumstellar Envelope



Channel maps of $^{12}CO(J=1-0)$ emission in the circumstellar envelope of the asymptotic giant branch star IRC+10216, obtained with BIMA+ NRAO 12-m (from Fong et al. 2003).

Model of a uniformly expanding shell (from Roelfsema 1989)



$v_{rad}(r) = \pm |\boldsymbol{v}_{exp}| [1 - (r^2/R^2)]^{0.5}$

Visualizing Spectral Line Data: Moment Analysis

The first three moments of a line profile yield, respectively: the total (frequency-integrated) intensity, the velocity field, and the velocity dispersion.

$$I_{\rm tot}(\alpha,\delta) = \Delta v \sum_{i=1}^{N_{\rm chan}} S_\nu(\alpha,\delta,\nu_i)$$

Total Intensity (Moment 0)

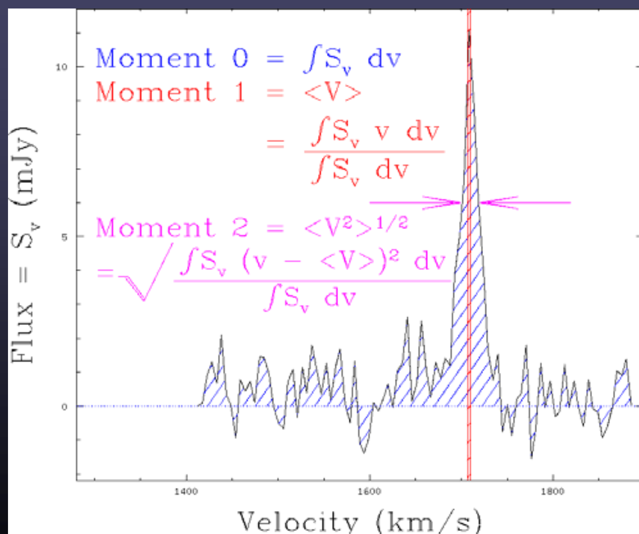
$$\overline{v}(\alpha,\delta) = \frac{\sum_{i=1}^{N_{\rm chan}} v_i\, S_\nu(\alpha,\delta,\nu_i)}{\sum_{i=1}^{N_{\rm chan}} S_\nu(\alpha,\delta,\nu_i)}$$

Intensity-Weighted Velocity (Moment 1)

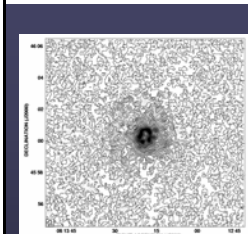
$$\sigma_v(\alpha,\delta) = \sqrt{\frac{\sum_{i=1}^{N_{\rm chan}} (v_i - \overline{v}(\alpha,\delta))^2\, S_\nu(\alpha,\delta,\nu_i)}{\sum_{i=1}^{N_{\rm chan}} S_\nu(\alpha,\delta,\nu_i)}}$$

Intensity-Weighted Velocity Dispersion (Moment 2)

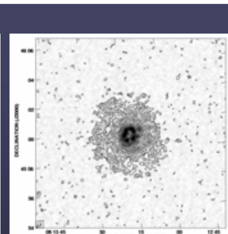
Visualizing Spectral Line Data: Moment Analysis



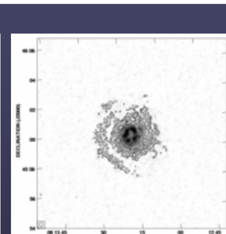
Computing Moment Maps



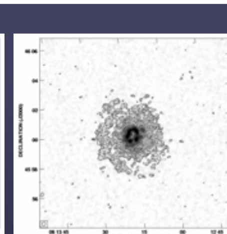
Straight sum of all channels containing line emission



Summed after clipping below 1σ



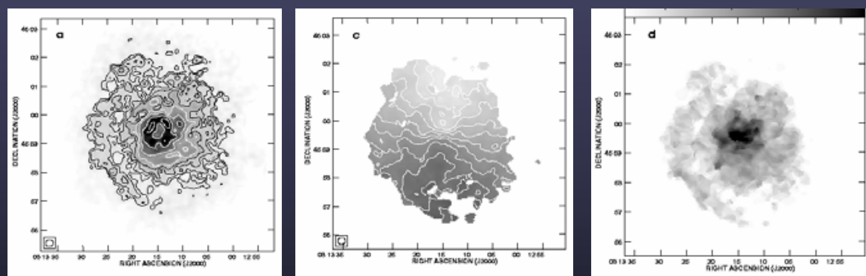
Summed after clipping below 2σ



Summed after clipping below 1 σ, but clipping is based on a version of the cube smoothed by factor of 2 in space and freq.

Four versions of a moment 0 (total intensity) map computed from the same data cube.

Visualizing Spectral Line Data: Moment Maps



Moment 0
(Total Intensity)

Moment 1
(Velocity Field)

Moment 2
(Velocity Dispersion)

Visualizing Spectral Line Data: Moment Maps–Some Cautions

Moment maps should be used with caution for quantitative analysis:

- Complex line profiles (double peaked, emission+absorption) can complicate the interpretation of moment maps.

- The details of moment maps are very sensitive to noise.

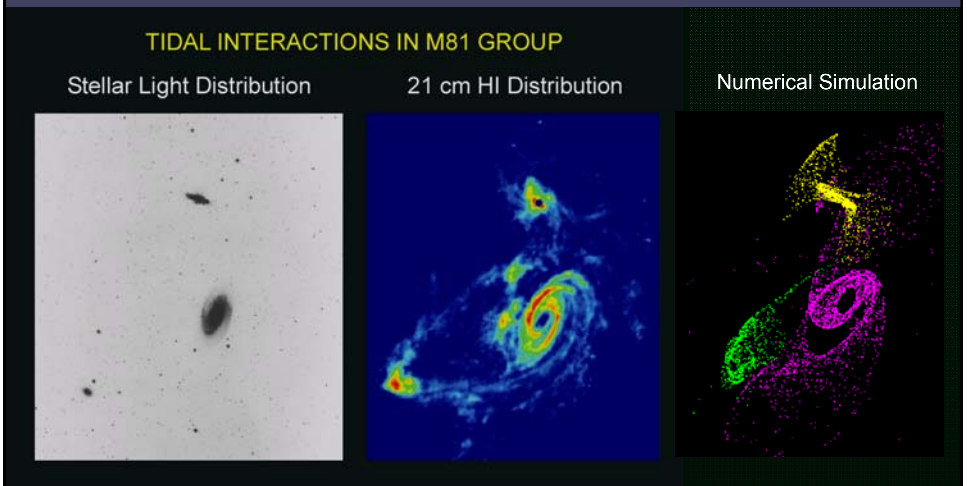
- Higher order moments are not independent of the lower-order moments and hence are increasingly susceptible to artifacts; use of higher noise cutoffs is recommended.

- Moment maps do not have easily-defined noise properties.

Moment maps should not be used directly for quantitative measurements (integrated line fluxes, rotation curves, etc.)

Use them as a guide for exploring/measuring features in the original data cube or comparison with other wavelengths/models.

Application of Moment Maps: Multiwavelength/ Model Comparisons



from Yun et al. (1994)