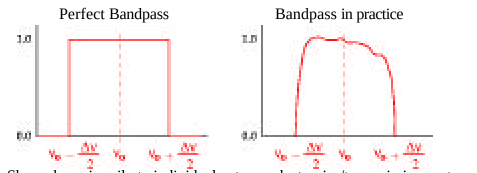
Spectral Line II: Calibration and Analysis

- Bandpass Calibration
- Flagging
- Continuum Subtraction
- Imaging
- Visualization
- Analysis

Spectral Bandpass:

- Spectral frequency response of antenna to a spectrally flat source of unit amplitude



- Shape due primarily to individual antenna electronics/transmission systems (at VLA anyway)
- Different for each antenna
- Varies with time, but much more slowly than atmospheric gain or phase terms

Bandpass Calibration

$$\tilde{V}_{ij}(\nu,t) = G_{ij}(\nu,t)\, V_{ij}(\nu,t) \qquad (5\text{-}4)$$

Frequency dependent gain variations are much slower than variations due pathlength, etc.; break G_{ij} into a rapidly varying frequency-independent part and a frequency dependent part that varies slowly with time

$$G_{ij}(\nu,t) = G_{ij}^c(t)\, B_{ij}(\nu,t) \qquad (12\text{-}1)$$

$G_{ij}(t)$ are calibrated as in chapter 5. To calibrated $B_{ij}(n)$, observe a bright source that is known to be spectrally flat

$$\tilde{V}_{ij}(\nu,t) = G_{ij}^c(t)\, B_{ij}(\nu)\, V_{ij} \qquad (1)$$

measured *independent of ν*

Bandpass Calibration *(cont'd)*

$$\tilde{V}_{ij}(\nu,t) = G_{ij}^c(t)\, B_{ij}(\nu)\, V_{ij} \qquad (1)$$

Sum both sides over the "good part" of the passband

$$\sum \tilde{V}_{ij}(\nu,t) = G_{ij}^c(t)\, V_{ij} \sum B_{ij}(\nu) \qquad (2)$$

Divide eqn. 1 by eqn. 2; this removes the effects of the atmosphere and the structure of the source, leaving only the spectrally variable part. The sum of the observed visibilities over the "good part" of the passband is called *"Channel Zero"*

$$\frac{B_{ij}(\nu)}{\sum B_{ij}(\nu)} = \frac{\tilde{V}_{ij}(\nu,t)}{\sum \tilde{V}_{ij}(\nu,t)} = \frac{\tilde{V}_{ij}(\nu,t)}{Ch.\,0} \qquad (3)$$

Bandpass Calibration *(cont'd)*

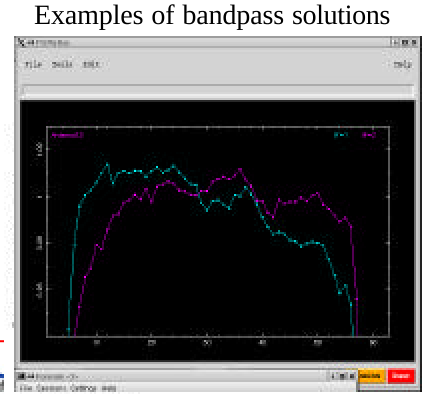
Most of frequence dependence is due to antennae response (*i.e.*, not the atmosphere or correlator), so break $B_{ij}(n)$ into contributions from antenna *i* and antenna *j*

$$B_{ij}(\nu) = b_i(\nu)\, b_j^*(\nu) \qquad (12\text{-}2)$$

$$b_i(\nu)\, b_j^*(\nu) = \frac{\tilde{V}_{ij}(\nu,t)}{Ch.\,0} \qquad (4)$$

27 unknowns, 351 measureables, so solve at each measured frequency. Compute a separate solution for each observation of the bandpass calibrator.

Examples of bandpass solutions



Checking the Bandpass Solutions

- Should vary smoothly with frequency
- Apply BP solution to phase calibrator - should also appear flat
- Look at each antenna BP solution for each scan on the BP calibrator - should be the same within the noise

Bandpass Calibration: Get it right!

- Because $G_{ij}(t)$ and $B_{ij}(n)$ are separable, multiplicative errors in $G_{ij}(t)$ (including phase and gain calibration errors) can be reduced by subtracting structure in line-free channels. Residual errors will scale with the peak remaining flux.
- Not true for $B_{ij}(n)$. Any errors in bandpass calibration will always be in your data. Residual errors will scale like continuum fluxes in your observed field

Strategies for Observing the Bandpass Calibrator

- Observe one *at least* twice during your observation (doesn't have to be the same one). More often for higher spectral dynamic range observations.
- Doesn't have to be a point source, but it helps (equal S/N in BP solution on all baselines)
- For each scan, observe BP calibrator long enough so that uncertainties in BP solution do not significantly contribute to final image

$$\Delta t_{BPcal} = 9 \times \left(\frac{S_{cont}}{S_{BPcal}}\right)^2 \Delta t_{source}$$

Flagging Your Data

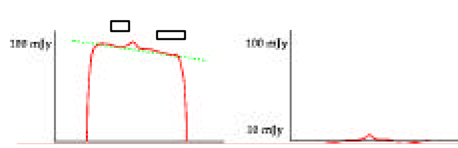
- Errors reported when computing the bandpass solution reveal a lot about antenna based problems; use this when flagging continuum data.
- Bandpass should vary smoothly; sharp discontinuities point to problems.
- Avoid extensive frequency-dependent flagging; varying UV coverage (resulting in a varying beam & sidelobes) can create very undesirable artifacts in spectral line datacubes

Continuum Subtraction

- At lower frequencies (X-band and below), the line emission is often much smaller than the sum of the continuum emission in the map. Multiplicative errors (including gain and phase errors) scale with the strength of the source in the map, so it is desirable to remove this continuum emission before proceeding any further.
- Can subtract continuum either before or after image deconvolution. However, deconvolution is a non-linear process, so if you want to subtract continuum after deconvolution, you must clean very deeply.

Continuum Subtraction: basic concept

- Use channels with no line emission to model the continuum & remove it
- Iterative process: have to identify channels with line emission first!



Continuum Subtraction: Methods

- **Image Plane** (IMLIN): First map, then fit line-free channels in each pixel of the spectral line datacube with a low-order polynomial and subtract this
- **UV Plane:** Model UV visibilities and subtract these from the UV data before mapping

  (UVSUB): Clean line-free channels and subtract brightest clean components from UV datacube

  (UVLIN): fit line-free channels of each visibility with a low-order polynomial and subtract this

Continuum Subtraction: Trade offs

- UVSUB:
  + easiest way to remove far-field sources properly.
  - depends on deconvolution
  - computationally expensive
- IMLIN:
  + can make work on cubes with few line-free channels, but spatially confined emission
  + works better than UVLIN on more distant continuum sources
  - cannot automatically flag data

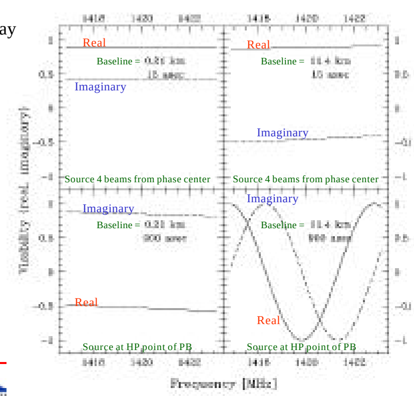
Continuum Subtraction: Trade offs

- UVLIN: visibility of a source at a distance Θ from phase center observed on baseline b_{ij} is:

  $$V_{ij} = \cos(2\pi \nu b_{ij} \Theta / c) + i \sin(2\pi \nu b_{ij} \Theta / c)$$

  For small b_{ij}, Θ and for a small range of ν, goes like 1 or linearly with ν
  + enables automatic flagging of anomalous points
  + can shift data to bright continuum source before fitting
  - since visibilities contain emission from all spatial scales, cannot have *any* line emission in fitted channels
  - poor fit at larger baselines and at large Θ

B-array



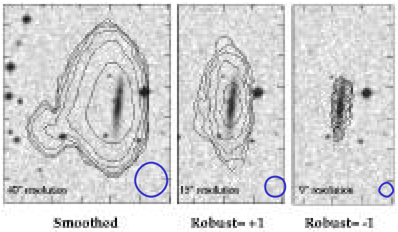
Continuum Subtraction: One Recommended Procedure

- Make a large continuum map to identify far field continuum sources
- UVLIN large number of channels on either end of the passband and map all channels
- Examine cube and identify channels with line emission
- Identify whether sidelobes from strong continuum sources are creating artifacts
  - one source: UVLIN with a shift to continuum source
  - more than one: UVSUB small number of components, then UVLIN
  - Sun - use Sault method
- Only IMLIN if emission is in most channels but localized in space, or several far-field continuum sources with nearby emission

Mapping Your Data

- Choice of weighting function trades off sensitivity and resolution
- We are interested in **BOTH** resolution (eg, kinematic studies) and sensitivity (full extent of emission)

Mapping Considerations:
trade off between resolution and sensitivity



Measuring the Integrated Flux

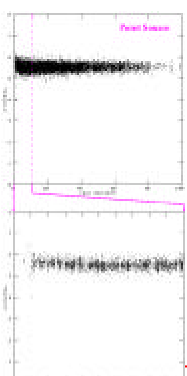
- Interferometers do not measure the visibilities at zero baseline spacings; therefore they do not measure flux

$$F(u,v) = \int\int f(x,y)\, e^{-2\pi i (ux+vy)}\, dx\, dy$$

$$u = 0,\ v = 0, \Rightarrow$$

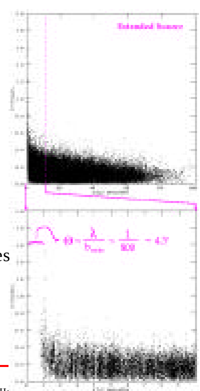
$$F(0,0) = \int\int f(x,y)\, dx\, dy = \text{integrated flux}$$

- Must interpolate zero-spacing flux, using model based on flux measured on longer baselines (ie, image deconvolution)



Not a difficult interpolation for point sources

But can lead to large uncertainties for extended sources

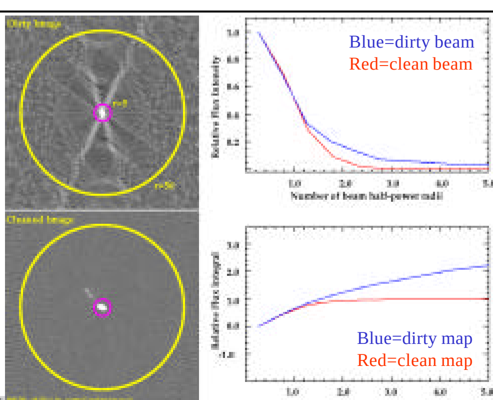


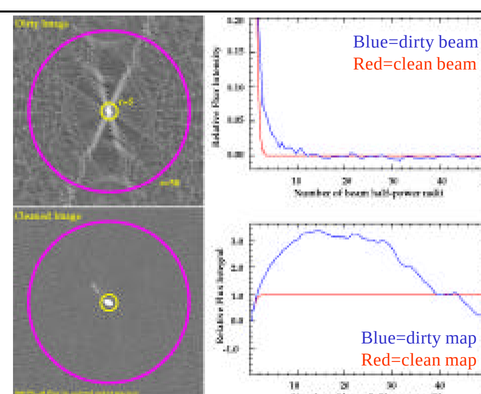
Measuring Fluxes

- Deconvolution leads to additional uncertainties, because Cleaned map is combination of clean model restored with a Gaussian beam (brightness units of Jy per clean beam) plus uncleaned residuals (brightness units of Jy per dirty beam)

$$S_{true} = S_{model} + S_{residuals}$$

- Cleaned beam area ≠ Dirty beam area





How do you measure flux?

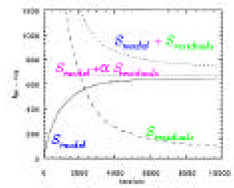
- Can get approximate correction factor by cleaning each map twice, to two different levels, and calculating an empirical correction factor, a

$$S_{true} = S_{model} + \alpha\, S_{residuals}$$

$$S_{model} = \sum_{i=0}^{N_{max}} CC_i$$

$$\alpha = -\frac{S_{model}^{N_{max1}} - S_{model}^{N_{max2}}}{S_{residuals}^{N_{max1}} - S_{residuals}^{N_{max2}}} \approx \frac{(\text{area of clean beam})}{(\text{area of dirty beam})}$$

Measuring flux



- However, a will depend on size of emitting region and area measured, so needs to be computed for each channel individually

(Jörsäter & van Moorsel, 1995, AJ, 110, 2037)

How deeply to clean

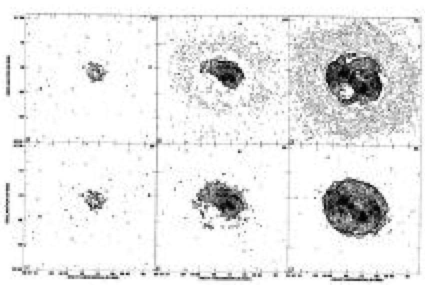
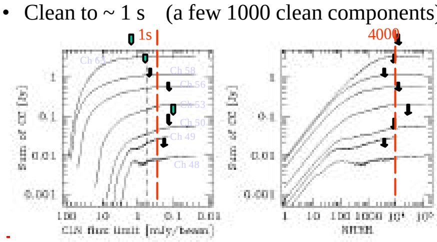


Figure 13-6. HI in the face-on spiral galaxy NGC 1058: a sampling of channel maps. The top row shows dirty maps, the bottom row CLEANed images. Note the large negative bowl in the dirty maps with the most extended emission. Contours are $4.2^{n/2}\sigma$, where σ is the rms noise (0.585 mJy/beam) and $n = 3, 4, \ldots$.

How deeply to clean

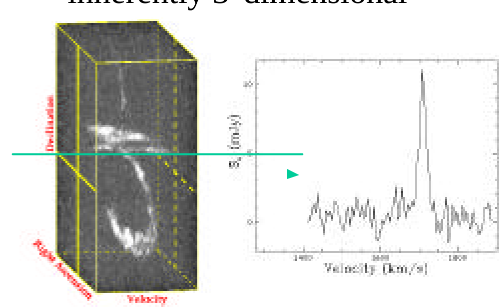
- Best strategy is to clean each channel deeply - clean until flux in clean components levels off.
- Clean to ~ 1 s (a few 1000 clean components)



Spectral Line Visualization and Analysis

Astronomer: Know Thy Data

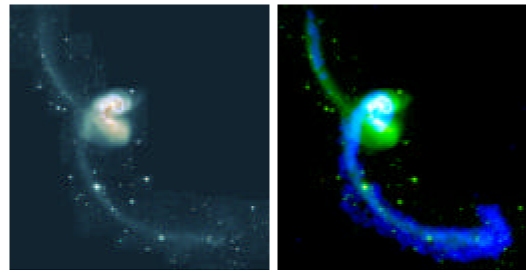
Spectral Line Maps are inherently 3-dimensional



For illustrations, You must choose between many 2-dimensional projections

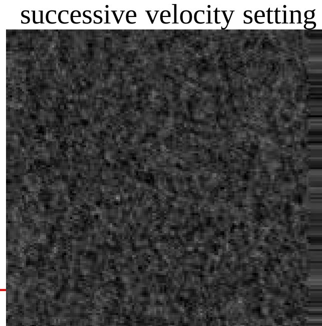
- 1-D Slices along velocity axis = line profiles
- 2-D Slices along velocity axis = channel maps
- Slices along spatial dimension = position velocity profiles
- Integration along the velocity axis = moment maps

Examples given using VLA C+D-array observations of NGC 4038/9: "The Antennae"

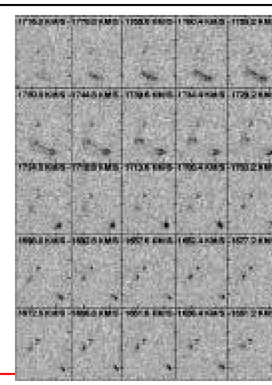


"Channel Maps"

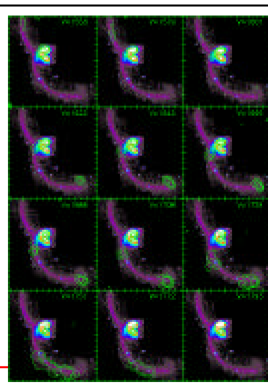
spatial distribution of line flux at each successive velocity setting



Greyscale representation of a set of channel maps



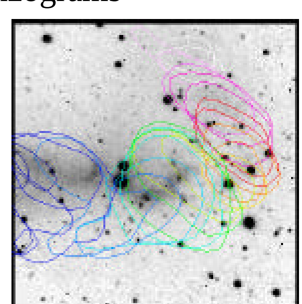
Emission from channel maps contoured upon an optical image



"Renzograms"

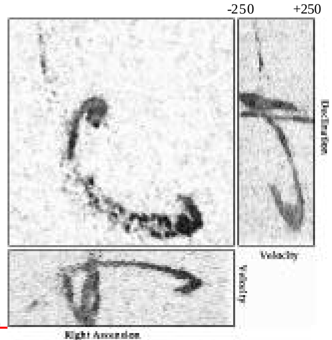
- A single contour from a series of channel maps, color coded according to velocity

(blue=low velocity, red=high velocity)

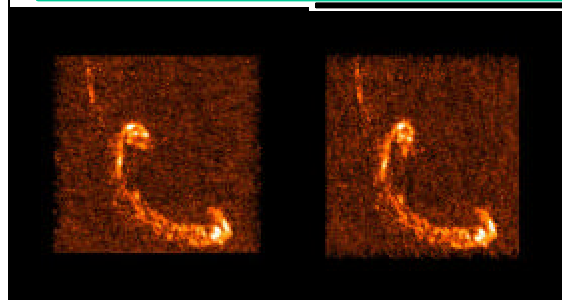


Position-Velocity Profiles

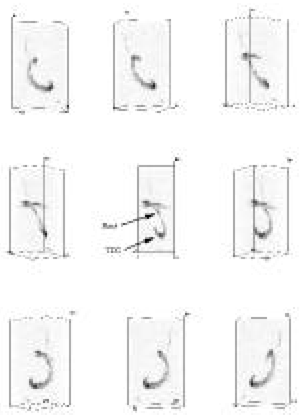
- Slice or Sum the line emission over one of the two spatial dimensions, and plot against the remaining spatial dimension and velocity
- Susceptible to projection effects



Rotating datacubes gives complete picture of data, noise, and remaining systematic effects



- Rotations emphasize kinematic continuity and help separate out projection effects
- However, not very intuitive



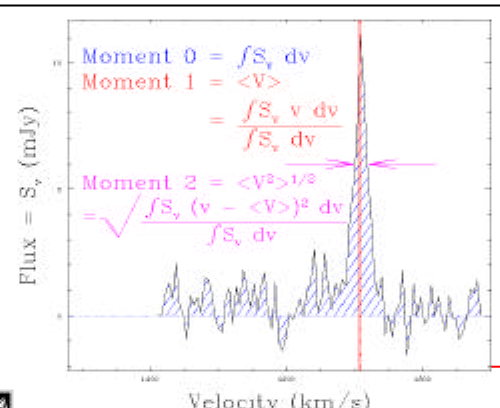
Spectral Line Analysis

- How you analyze your data depends on what is there, and what you want to show
- ALL analysis has inherent biases

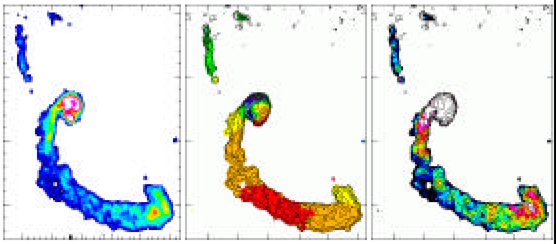
"Moment" Analysis

Integrals over velocity

- 0th moment = total flux
- 1st moment = intensity weighted (IW) velocity
- 2nd moment = IW velocity dispersion
- 3rd moment = skewness or line asymmetry
- 4th moment = curtosis



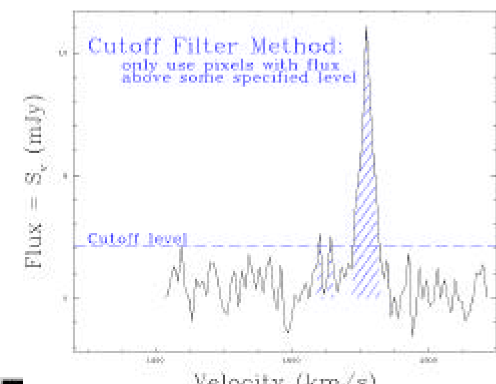
Moment Maps

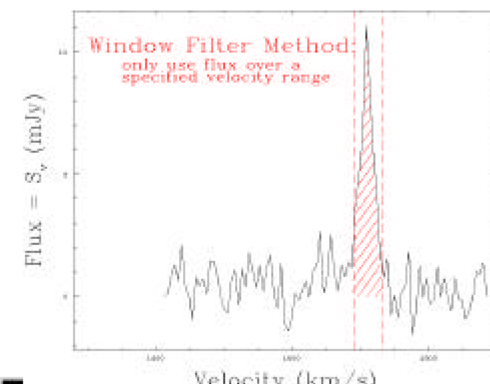


Zeroth Moment	First Moment	Second Moment
Integrated flux	mean velocity	velocity dispersion

Unwanted emission can seriously bias moment calculations

- Put conditions on line flux before including it in calculation.
  - **Cutoff method:** only include flux higher than a given level
  - **Window method:** only include flux over a restricted velocity range
  - **Masking method:** blank by eye, or by using a smoothed (lower resolution, higher signal-to-noise) version of the data

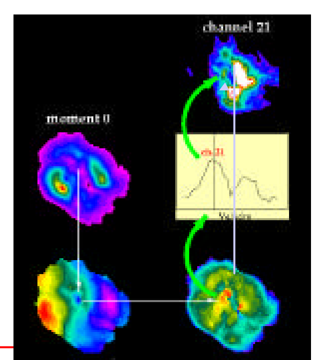




Higher order moments can give misleading or erroneous results

- Low signal-to-noise spectra
- Complex line profiles
  - multi-peaked lines
  - absorption & emission at the same location
  - asymmetric line profiles

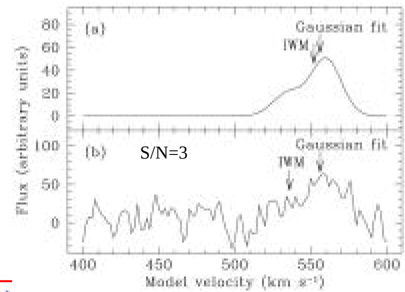
Multi-peaked line profiles make higher order moments difficult to interpret



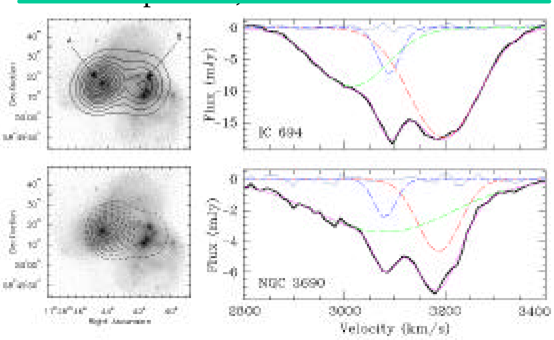
“Moment” Analysis: general considerations

- Use higher cutoff for higher order moments (moment 1, moment 2)
- Investigate features in higher order moments by directly examining line profiles
- Calculating moment 0 with a flux cutoff makes it a poor measure of integrated flux

Intensity-weighted Mean (IWM) may not be representative of kinematics



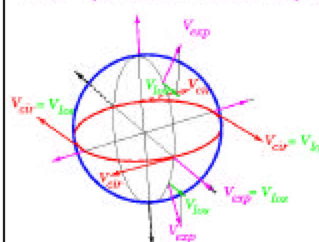
For multi-peaked or asymmetric line profiles, fit Gaussians



Modeling Your Data

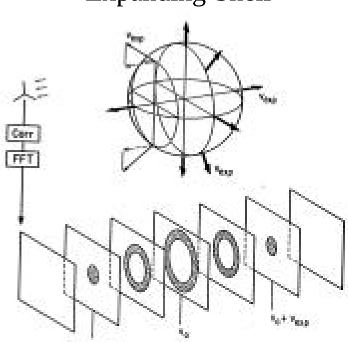
You have 1 more dimension than most people - use it

$$V_{los} = V_{sys} + V_{cir}(R) \sin i \cos\Theta + V_{exp}(R) \sin i \sin\Theta + V_z(R,\Theta) \cos i$$

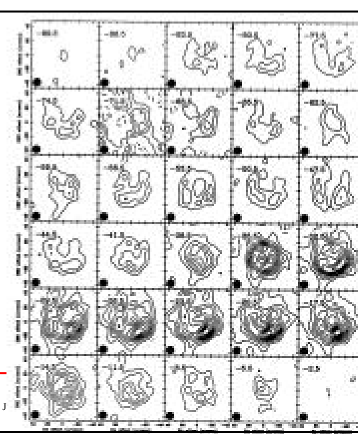


- Rotation Curves
- Disk Structure
- Expanding Shells
- Bipolar Outflows
- N-body Simulations
- etc, etc

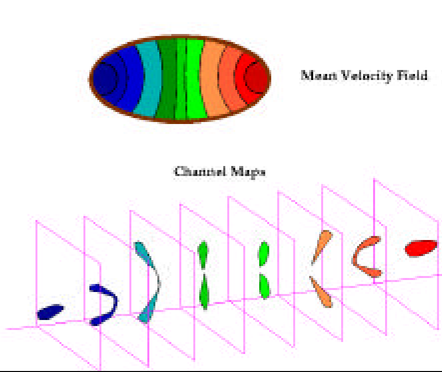
Simple 2-D models: Expanding Shell



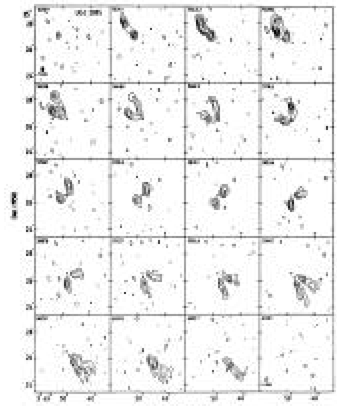
Example of Channel Maps for Expanding Sphere



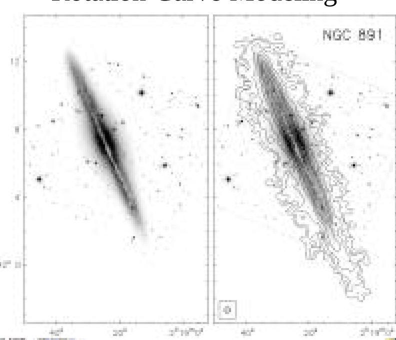
Simple 2-D model: Rotating disk



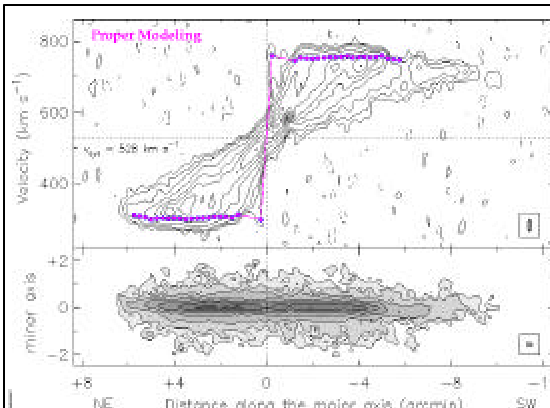
Example of Channel Maps for Rotating disk



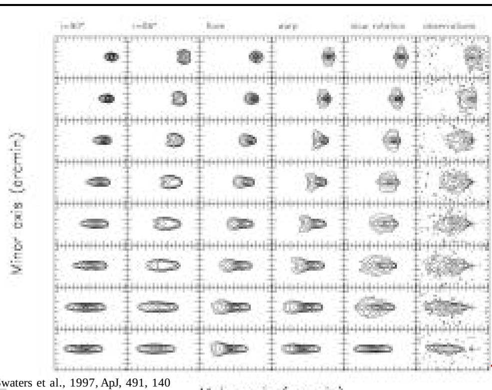
Matching Data in 3-dimensions: Rotation Curve Modeling



Swaters et al., 1997, ApJ, 491, 140

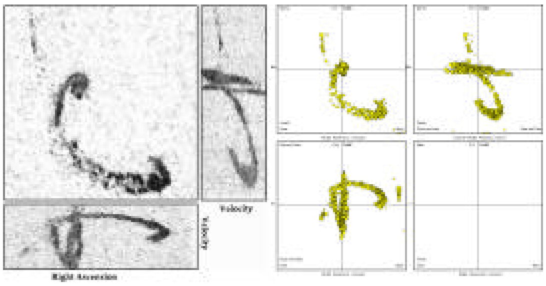


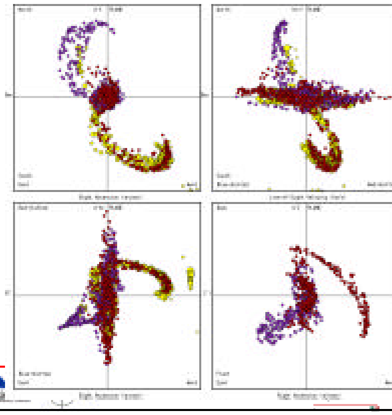
Swaters et al., 1997, ApJ, 491, 140

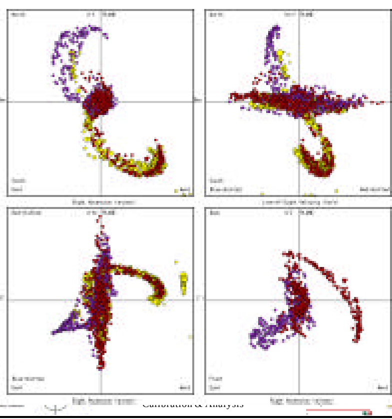


Swaters et al., 1997, ApJ, 491, 140

Matching Data in 3-dimensions: N-body simulations







Conclusions:

Spectral line mapping data is the coolest stuff I know