Modelling the Velocity Width Distribution Function for Dusty Galaxies at High Redshift

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Background

At high redshifts and early cosmological time, sub-millimeter galaxies (SMGs) are dusty galaxies with luminosities powered primarily by star formation, and quasi-stellar objects (QSOs) are systems whose luminosities are powered mostly by accretion onto supermassive black holes. Velocity widths of CO rotational lines can be obtained from the gas reservoirs that fuel star formation in SMGs and the accretion onto black holes in QSOs. The galaxy's inclination angle toward Earth affects the measured velocity widths, with face-on inclinations giving the lowest velocity measurements and edge-on inclinations giving the highest measurements.

Methodology

To account for this inclination effect on the velocity widths (Δv), a cumulative distribution function (CDF) is used to model the observed velocity width data set. The CDFs below have two unknown parameters, V_{rot} and V_{disp}.

$$CDF(\Delta v) = 1 - \frac{1}{V_{rot}}\sqrt{{V_{disp}}^2 + {V_{rot}}^2 - (\Delta v)^2}$$

Equation 1 – CDF model for galaxies with no inclination bias

$$CDF(\Delta v) = \frac{(\Delta v)^2 - {V_{disp}}^2}{{V_{rot}}^2}$$

Equation 2 – CDF model for galaxies selected with some face-on inclination bias

The V_{disp} and V_{rot} parameters are changed into two new parameters, V_{min} and V_{max}, corresponding to the lower and upper boundaries of the domain of Δv.

$$V_{disp} = V_{min} \qquad V_{rot} = \sqrt{{V_{max}}^2 - {V_{min}}^2}$$

Equations 3 (left) & 4 (right) – Relationship between MCMC parameters V_{min} and V_{max} and the dispersion and rotational velocities

To find the V_{min} and V_{max} values that give the best match to the observed data, Markov chain Monte Carlo (MCMC) methods are used. These methods explore a given set of parameters through a step-by-step process that moves toward the parameter values that give the best match between the model and the observed data. Using this method in conjunction with the velocity width model enables finding the V_{min} and V_{max} values that give the best fit between the modelled CDF and the observed data.

To gauge the strength of inclination bias, equation 5 below includes the parameter c, with $c \geq 0$ and a larger c value corresponding to greater face-on inclination bias ($c = 0$ and $c = 1$ give equations 1 and 2, respectively).

$$CDF(\Delta v) = 1 - \left(\frac{{V_{disp}}^2 + {V_{rot}}^2 - (\Delta v)^2}{{V_{rot}}^2}\right)^{\frac{c+1}{2}}$$

Equation 5 – CDF equation used to determine strength of face-on inclination bias

To allow two types of a galaxies to be used in the model, two CDF models with their own set of V_{min} and V_{max} parameters are used. For each galaxy type to compose half of the galaxies in the model, each sub-population's CDF is divided by 2. An MCMC run is conducted for the two sets of V_{min} and V_{max} parameters, and the two sub-populations' CDFs are added together to make the main CDF, which is compared to the data.

To replace the V_{max} parameter with M_{BH}, the mass of the black hole central in a QSO, the two equations below are used.

$$\log_{10}\left(\frac{M_{BH}}{\mathrm{M}_{\odot}}\right) = 8.14 + 3.38\log_{10}\left(\frac{\sigma_*}{200\ \mathrm{km\ s^{-1}}}\right)$$

$$\log_{10}\sigma_* = 1.26\log_{10}V_{rot} - 0.78$$

Equations 6 (above, from Caglar et al. 2020) & 7 (below, from Ho 2007) – Equations used to relate M_{BH} to V_{rot} through the stellar dispersion velocity (σ_*)

Results

Analyses were performed for a literature sample of QSOs (Figures 1 and 2) and for a large sample of galaxies from Herschel Space Observatory imaging surveys with CO redshifts (Figures 3, 4, 5, and 6).

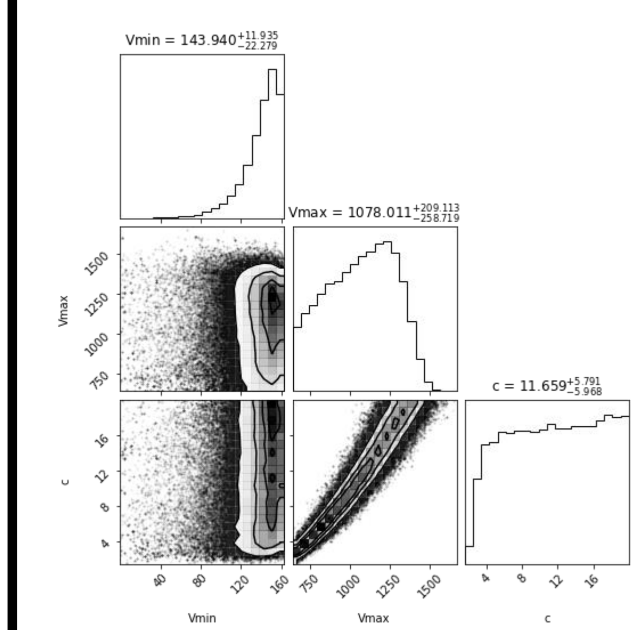

Figure 1 – Corner plot and histograms from an MCMC run using equation 5 showing most probable values of the parameters V_{min}, V_{max}, and c.

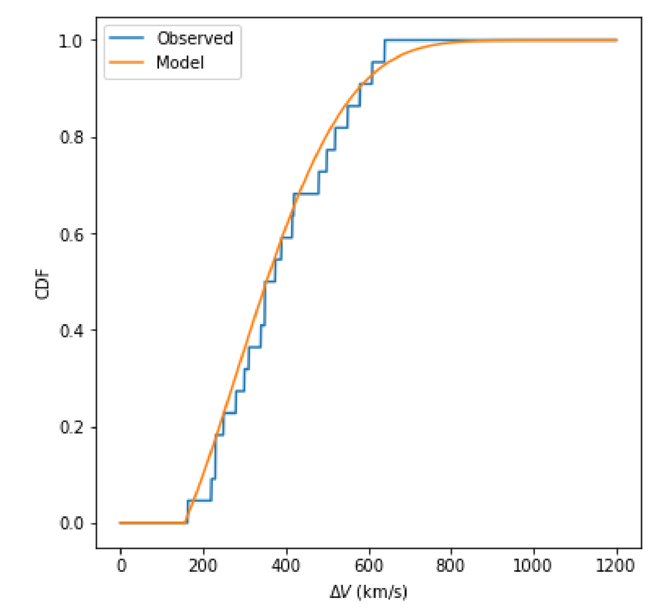

Figure 2 – Resulting CDFs after plugging in modes of histograms from figure 1 into equation 5.

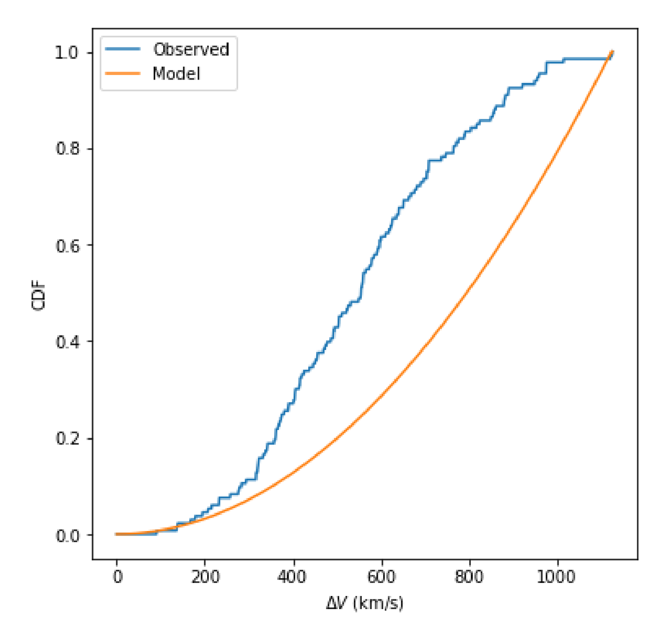

Figure 3 – Modelled and observed CDFs resulting from an MCMC analysis using the single-population model with equation 2.

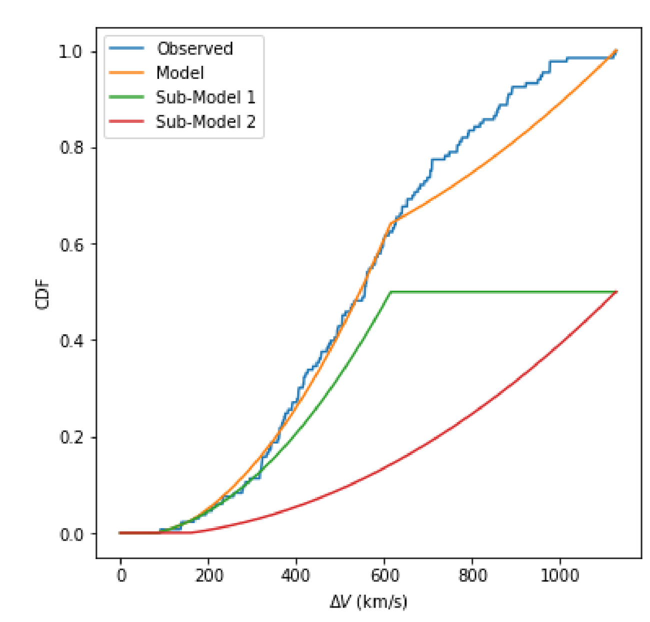

Figure 4 – Modelled and observed CDFs resulting from an MCMC analysis using the two-population model with equation 2.

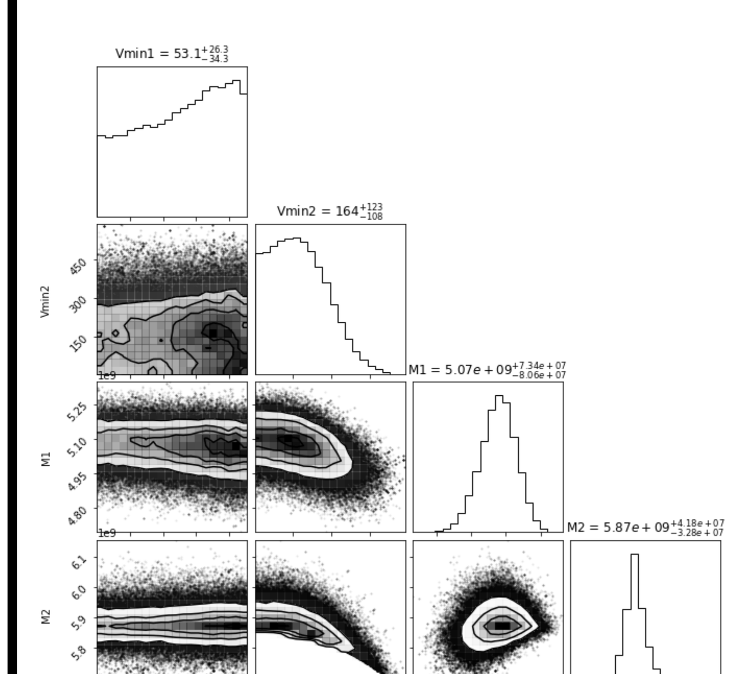

Figure 5 – Corner plot from an MCMC run finding the most probable values of the V_{min} and M_{BH} parameters using the two-population model.

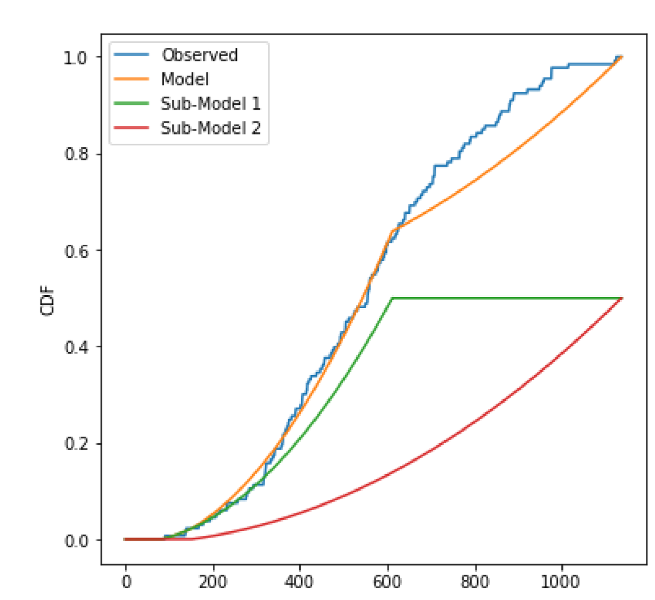

Figure 6 – Resulting CDFs of each sub-galaxy after using their parameter modes from figure 5; the main CDF is obtained by adding the two sub-populations' CDFs together.

Conclusions

- Single-population model gives strong match to observed data only with improbably high face-on inclination bias
- Two-population model gives better match to observed data than single-population model

Future Work

- Relate velocity widths to new galactic properties
  - Geometry of dusty tori in QSOs
- Create model allowing more than two types of galaxies

References

- Caglar, T., Burtscher, L., Brandl, B., et al. 2020, A&A, 634, A114
- Ho, L. C. 2007, ApJ, 669, 821