Star Forming Galaxies in the Merging RCS 2319+00 Supercluster

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Objectives

- To map the distribution of star forming galaxies in the merging RCS 2319+00 supercluster.
- To better understand how star forming galaxies are affected by large-scale cosmological structure formation.

Introduction

I. Cosmological Structure Formation

- Observations of the cosmic microwave background (CMB) indicate that at early times the universe was hot, dense, and **homogeneous** [1].
- Looking into the sky, however, we observe structures across a wide range of scales (stars, galaxies, galaxy clusters, *etc.*). *How did these structures form?*
- The current paradigm is **hierarchical** in that large-scale structures are thought to form from small-scale ones (*i.e.*, stars → galaxies → galaxy clusters → superclusters) [2].

II. The RCS 2319+00 Supercluster

- RCS 2319+00 is located at $\mathbf{z \sim 0.9}$. During this epoch, star formation rates (SFRs) were ∼10 times higher than today [3]. Recent studies suggest, however, that **star formation becomes quenched** in galaxies as they fall into the cores of clusters [4][5].
- Comprising three high-mass galaxy clusters in close proximity, it is a supercluster in the process of assembly.

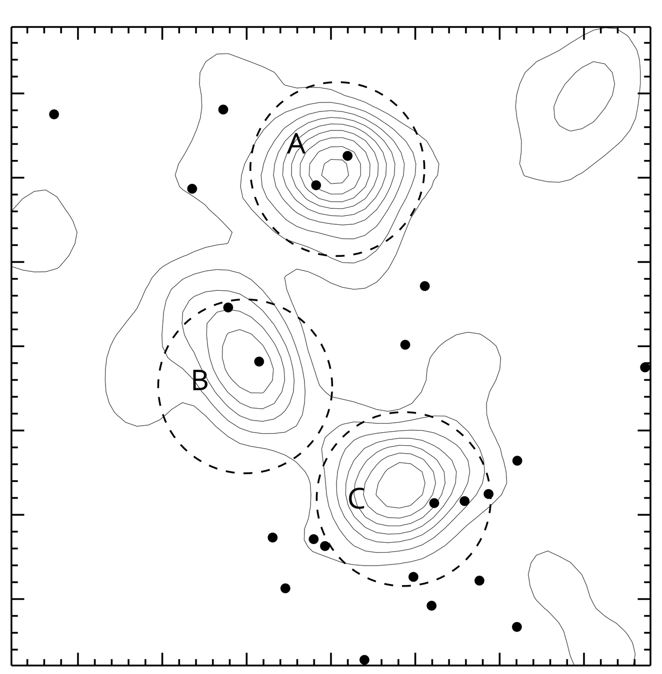

Figure 1: X-ray map of RCS 2319+00, borrowed from [6].

Data

Two datasets are used in conjunction to create profiles detailing the coordinates, redshifts, and 250μm fluxes of the most luminous infrared (IR) galaxies in the RCS 2319+00 supercluster:

- A multiwavelength spectroscopic catalogue including data from six observing runs with five instruments. It contains the redshifts and coordinates of 327 high-confidence targets in the broad membership range $\mathbf{0.858 \le z \le 0.946}$ [6], but not their 250μm fluxes.
- An IR catalogue produced by the Herschel space observatory's Spectral and Photometric Imaging REceiver (SPIRE). It contains the coordinates and 250μm fluxes of 1086 objects, without redshift information.

These datasets overlap in a 50 × 50 arcminute region of the sky. A nearest-neighbour matching algorithm with a matching radius of 10 arcseconds yields **38 matches** between them. We therefore have the coordinates, redshifts, and 250μm fluxes of 38 members of the RCS2319+00 supercluster.

Star Formation Rates

To determine the SFRs of the 38 identified IR galaxies, we first convert their 250μm fluxes to luminosities:

$$L = 4\pi d^2 F, \quad (1)$$

where d is a given galaxy's distance from Earth. In accounting for the effect cosmological expansion has on d, we take $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$, and $H_0 = 71$ km s^{-1} Mpc^{-1}. Next, we make use the following relationship (estimated in [7]):

$$\frac{SFR}{1 M_{Sun} yr^{-1}} = \frac{L_{FIR}}{2.2 \times 10^{36} W}, \quad (2)$$

where L_{FIR}, the far-IR luminosity of a galaxy, is the total luminosity integrated over the range $\mathbf{8\mu m \le \lambda \le 1000\mu m}$. Since we have the luminosity at only one point in this range, however, we cannot determine L_{FIR} directly for the members of RCS 2319+00. Instead, we turn to the template spectral energy distribution (SED) depicted in figure 2, which describes the energy output of a typical IR galaxy.

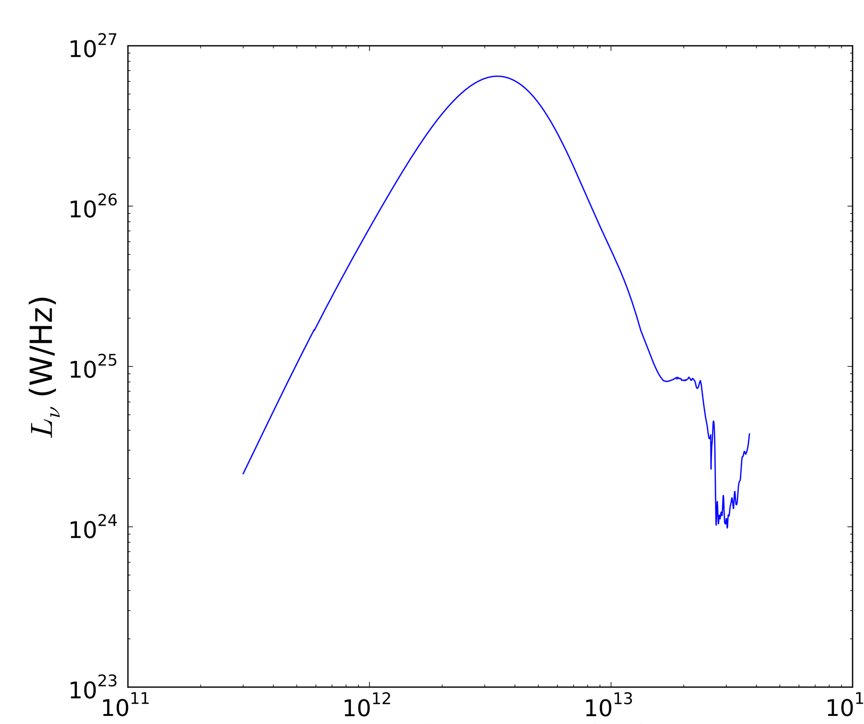

Figure 2: Luminous IR galaxy template SED, provided by [8]. The area under the curve represents the total IR luminosity L_{FIR}.

The SEDs of the 38 member infrared galaxies are assumed to have the same form as that in figure 2, scaled according to the ratio between the 250μm luminosity of the member galaxy and that of the template galaxy. For example, if a given member galaxy is twice as luminous at 250μm as the template galaxy, the whole template SED is scaled up by a factor of two. L_{FIR} is then determined by taking the area under the curve.

Mapping RCS 2319+00

I. Positions

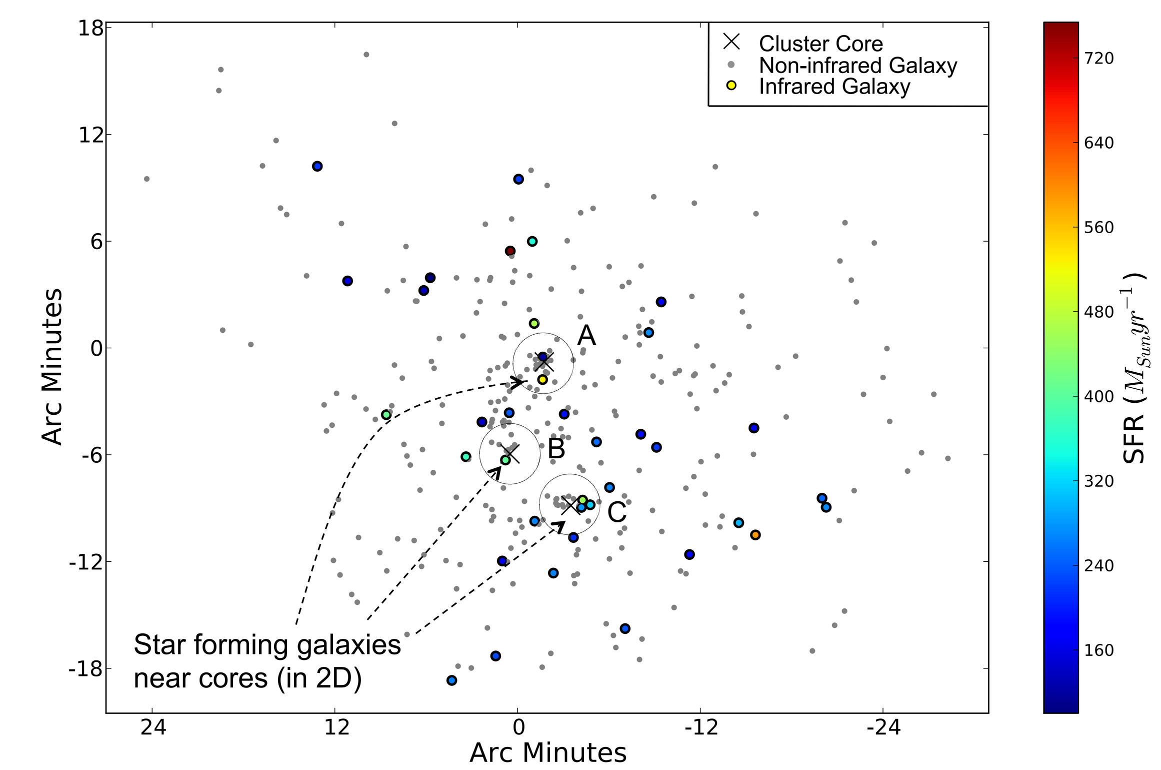

Figure 3: A map of RCS 2319+00. The dotted circles represent 1.0 Mpc (2 arcminute) radii centred on the supercluster's three cores, labeled A through C. 38 identified infrared members are plotted as black-bordered, coloured circles. The remaining 289 non-infrared members are plotted as grey circles.

Figure 3 demonstrates that six luminous infrared (star forming) galaxies producing a total of **∼2100 solar masses per year** reside within 1.0 Mpc (in the plane of the sky) of the three cores of RCS 2319+00.

II. Velocities

Galaxy velocities relative to RCS 2319+00's cluster cores are determined by comparing the redshifts of the galaxies to those of the cores.

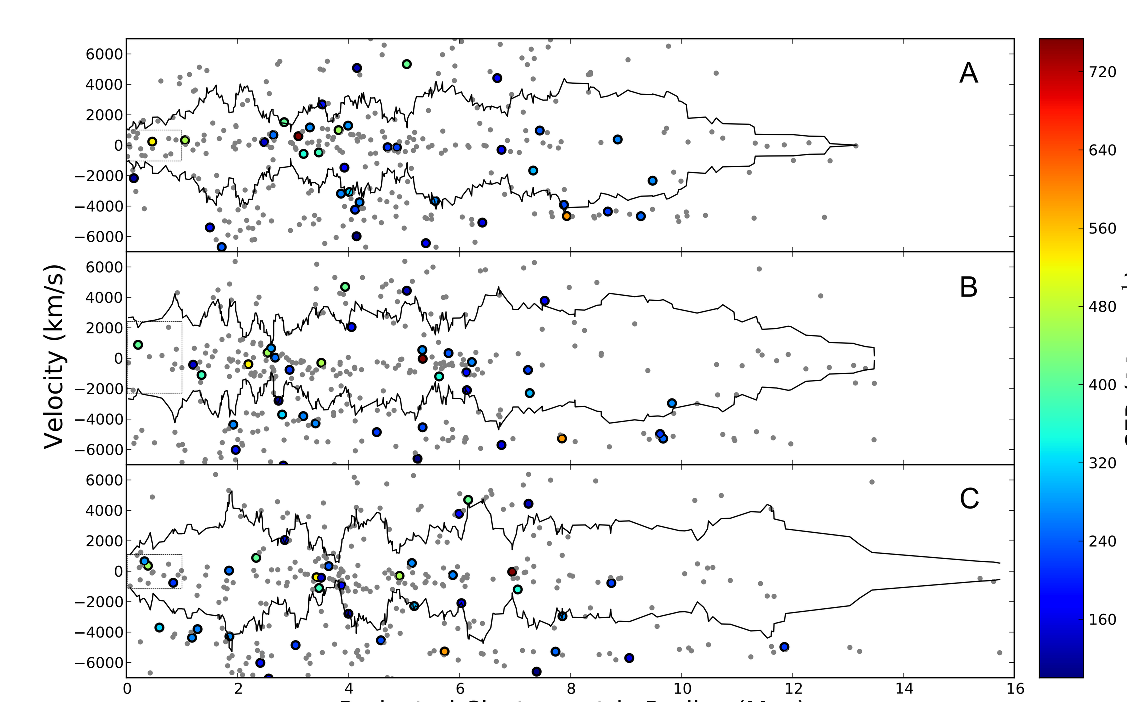

Figure 4: A diagram plotting 327 member galaxies' velocities along the line of sight relative to a cluster core against their distances from that cluster core, for each of the three cores labeled A through C. Symbols and colouring follow figure 3. The black lines are running averages of all points, reflected about the x-axis. The dotted boxes represent the 1.0 Mpc radii centred on the cores in Figure 3, bounded vertically by the running average lines.

Sources near the origin in figure 4 are close to a core and moving slowly relative to it, meaning they are likely to have been accreted long ago. One of the two star forming galaxies that appears in Figure 3 to reside in core A is revealed here to be moving quickly relative to the core, indicating that it may have arrived recently.

If six star forming galaxies really reside in RCS 2319+00's cores, it would indicate that they have managed to survive at least one free-fall time (the time it takes for a galaxy to fall from the outskirts of a cluster into the core) in the cluster environment. The gravitational free-fall time for a spherical cloud of matter is given in [9] as

$$t_{ff} = \left(\frac{3\pi}{32} \frac{1}{G\rho_0}\right)^{1/2}, \quad (3)$$

where ρ_0 denotes the average density of the cloud. Using this equation with densities provided by [6], we calculate a free-fall time of $\sim 1\times10^9$ years for each of the three clusters. This suggests that the mechanisms responsible for quenching star formation in galaxy clusters have characteristic time scales of at least $\sim 1\times10^9$ years. Furthermore, since five of the six star forming core candidates identified here exhibit low line of sight velocities relative to their respective cores, they may have survived multiple free-fall times while approaching rest in the cores.

Conclusion

We identify 38 star forming galaxies producing a total of $\sim 1.1\times10^4$ solar masses per year in the redshift range $0.858 \le z \le 0.946$ of the RCS 2319+00 supercluster. Six of these, forming a total of ∼2100 solar masses per year, appear to reside in the supercluster's cores, within 1.0 Mpc on the plane of the sky. Analysis of galaxy velocities suggests that five of the six were accreted at an early epoch, while the last may have arrived more recently. The presence of star forming galaxies in the supercluster's cores indicates that the galaxies have survived at least one free-fall time in the cluster environment, or $\sim 1\times10^9$ years. This would suggest that the processes responsible for quenching star formation in galaxy clusters occur over time scales of at least $\sim 1\times10^9$ years.

References

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