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# The Intracluster Stellar Population

We (upper-level undergraduates, if you will) are used to the concept of galaxies, full of stars, gas, and dust, sprinkled in clusters throughout the vast empty space of the observable universe. This oversimplified model ignores the population of stars (and other debris) that fills the space between galaxies - the intracluster stellar population. Discovering the source and prevalence of this intergalactic debris may help astronomers map the interactions of both baryonic and dark matter in proto-galaxies, helping broaden our understanding of the universe's earliest days.

In 1951, the ever-enigmatic Fritz Zwicky proposed intergalactic stars (IGS) ejected due to tidal interactions between galaxies as a the source of excess light between galaxies (Zwicky 1951). But evidence to substantiate this claim did not materialize until almost five decades later due to the difficulty both of detecting (comparatively) dull intergalactic stars at large distances and of differentiating this light from light from galaxies - it would be discovered later that the brightest intra-cluster light is less than 1% of the brightness of the night sky (Mihos, 2003). Studies in this period examining this light were unable to prove it came from stars, and searches for supernovae outside of galaxies were unsuccessful:

> …many observers concluding that the amount of intergalactic light could be attributed to low surface brightness galaxies, inaccurate subtraction of foreground stars and haloes of galaxies…Of the 13 supernovae detected…Crane, Tammann & Woltjer (1977) could associated all of them with galaxies. (Theuns & Warren, 1996)

Two studies from the late nineties provided the first evidence for intergalactic stars; Theuns & Warren identified planetary nebulae (PNe) in observations of the Fornax Galaxy cluster in 1996, and Ferguson, Tanvir, and von Hippel directly detected intergalactic stars in the Virgo Cluster in 1997.

Theuns & Warren imaged three fields of 5.9 arcsin$^2$ in the Fornax Cluster in the narrow, broad, and I bands at European South Observatory in Chile. Following dark and bias subtraction, flat-fielding, and cosmic ray elimination, the astronomers used the unique color of PNes (compared to galactic stars and compact galaxies) to identify ten strong candidates for intergalactic PNes; for each of these candidates, the difference between narrow and broad band magnitude was at least 3σ less than the population average. Using Ciardullo et. al.'s value for PNe density in M31, the astronomers then estimated a total surface brightness of intergalactic tidal debris of $1.0 \times 10^7 (L_B)_\odot$, per square arc minute, equivalent to about 40% of that of the Fornax Cluster's center (Theuns & Warren, 1996).

Further evidence was provided by Hubble Space Telescope images of a blank field in the Virgo Cluster. The Hubble Deep Field was used as a control (since, at faint limits, compact galaxies are indistinguishable from background stars), and, after noise was added to the sky images to match the noise in the HDF images, a clear discrepancy was shown between the Virgo field and the HDF. Figure 1 shows this discrepancy graphically, beginning at I = 26.8.

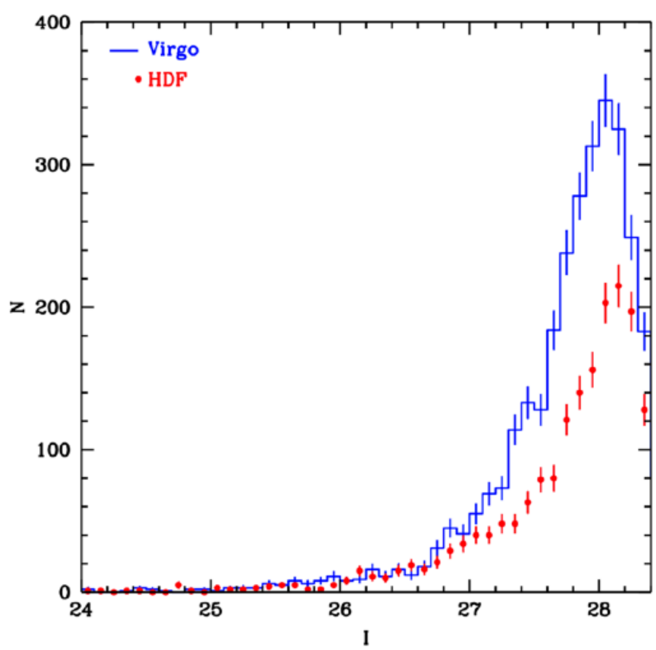


Figure 1: Comparison of Source Counts between blank field in Virgo Cluster and control HDF (Ferguson, Tanvir, von Hippel, 2008)

Because only 20 galactic foreground stars are expected at this brightness, the 600+ additional sources indicate the presence of intergalactic stars in this field. To determine what portion of light in the Virgo cluster comes from IGS, the astronomers attempted to categorize the total flux from this field by light color, based on the fact that the IGS were likely older stars (since elliptical and S0 galaxies are more abundant and have likely inhabited the center of the Virgo cluster for longer than spirals and irregulars). The resultant estimation is that 10% of light in this field comes from IGS (Ferguson, Tanvir, von Hippel, 2008). The authors state that the discrepancy between theirs and the aforementioned PNe study by Theuns & Warren is likely due to small-n statistics, inconsistent PNe density in stellar population models, or sample contamination by background emission-line galaxies.

Over the next few years, research into the topic was expanded by observing similar fields in searches for PNes, Novae, and other direct observation attempts. In 2006, Stanghellini, González-García, and Manchado developed and ran a number of simulations of elliptical galaxy collisions (or dry mergers), with the goal of comparing the resultant ejected mass proportions with the observed percentage of light from IGS. These simulations involved collisions between two elliptical galaxies of low-to-intermediate mass stars (0.5-8⊙) at $v = 414\ km/s$, with mass fraction and orbital mechanics as varied parameters. At its high extreme (high-energy hyperbolic orbit and $M_2/M_1 = 1$), 21% of the initial mass was left unbound as IGS, and at its low extreme (low-energy parabolic orbit, $M_2/M_1 = 1$), 5.5% was left unbound. After modeling the luminosity change of this unbound mass (due to progression of these stars to red-giant stage and beyond), the astronomers determined the proportion of luminosity from unbound stars to galactic stars ( $L_{IGS}/L_G$) to be 38% at its upper limit and 17% at its lower limit (Stanghellini et al., 2006).

Results from most of the studies on IGS prevalence in the years preceding this simulation fall within this limit. Differences between lower and upper limits are explained by differences in collision velocity; a PNe study encompassing much of the Virgo cluster (Feldmeier et al., 2004) found $L_{IGS}/L_G$ of 16%, but a similar study of velocity dispersions of PNes in Virgo identified fields of much lower dispersion velocities ($v = 247\ km/s$) than expected (Arnaboldi et al., 2004), possibly explaining the lower starlight ratio. In a study (in the same area of the Fornax cluster studied by Theuns & Warren in 1996), the density function of novae, which are useful as standard candles, was used to estimate an $L_{IGS}/L_G$ of 16-41% (Neill et al., 2005), aligning closely with the results of the simulation.

As interest in IGS grew, we began to look closer to home for populations of individual unbound stars. HE 0437-5439, a hyper-velocity IGS is flying through space, alone, at nearly 810 $km/s$ relative to the Galactic Center. This makes it a good proxy for IGS that aren't part of a group, as we would expect from galaxy-galaxy interactions. Brown et al. examined its absolute proper-motion with Hubble Space Telescope data, finding that its velocity points directly away from the center of the Milky Way (see Figure 2). Because its surface gravity, effective temperature, and rotation indicate it is a $9M_{\odot}$ main sequence star, its supposed lifetime of 20 Myr far exceeds the time required to travel from the galactic center to its current location at its current velocity. The astronomers concluded that

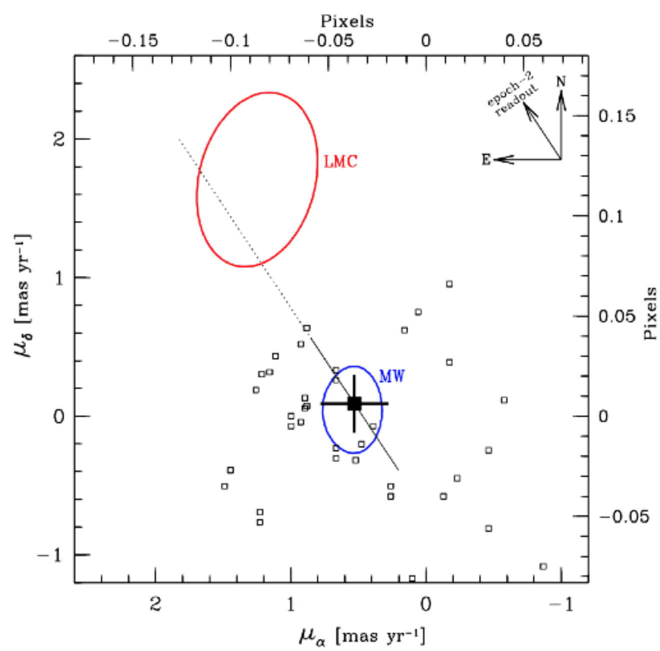


Figure 2: Plot of the absolute proper motion of HE 0437-5439 showing trajectory through center of Milky Way. 'MW' indicates Milky Way, 'LMC' indicates Large Magellanic Cloud' (Brown et al.)

it must be a blue straggler, a larger and more luminous star than those at the main sequence turnoff of HR-diagrams and a result of a merged binary pair. The only object compact and massive enough to eject a binary pair of this type, at this velocity, without disrupting the orbit or destroying one of the stars is a massive black hole, like the one at the center of the Milky Way galaxy. As a result, the astronomers conclude that HE 0437-5439 is the result of a merged binary pair that was ejected by the black hole at the galaxy's center (Brown et al., 2010).

Examinations of near IGS continued with the 2012 development of a method for identifying IGS between 300kpc and 2Mpc by Palladino et al. Using data from the Sloan Digital Sky Survey, these astronomers searched for red giants and supergiants in 'clean' areas of intergalactic space. Searching the sky for M7-M10 red giants in color band ranges $2.1 < r - i < 3.4$ and $1.3 < i - z < 2.2$, 677 possible IGS were identified as strong candidates for stars recently ejected from the Milky Way by either a method similar to the black-hole slingshot mentioned above, or other tidal stripping (Palladino et al., 2012). This method has flaws, since L or T dwarf stars fall into the color range used in the survey, and it is likely that there are far more dwarf stars than giant stars in any region of space. The SDSS lacks data on the metallicity of these stars - data which would help identify their spectral type and resolve the method's weakness.

Thus far, most of the discussion has detailed either the percentage of light coming from intergalactic stars, or the 'how they got there' of IGS - the mechanics of galaxy collisions or star ejections from galaxies due to black holes or other tidal forces. Some of the most modern research, however, indicates that there may be large concentrations of star forming regions outside of galaxies as a consequence of galactic interactions in compact groups.

Stephan's Quintet (SQ), the most accessible compact group of galaxies, contains two large barred spiral galaxies and two smaller elliptical galaxies (the fifth galaxy is not a true member of the compact group by proximity, it only appears close to the other members). The two central galaxies (NGC 7318a and 7318b) are colliding, and generating a shockwave in the intergalactic gas. Duarte Puertas et. al., using the Canada-France-Hawaii Telescope, analyzed data from the imaging Fourier transform spectrometer SITELLE to identify and describe other large radial-velocity regions inside the cluster. Astronomers first identified Hα regions throughout the field of view, then filtered out those which did not fit the radial velocity profile of SQ to eliminate regions that aren't part of the kinematic cluster, leaving 176 remaining SQ Hα regions (see Figure 3). Out of these regions, 22 have line profiles with multiple kinematic components (Duarte Puertas et al., 2019). This paints a picture of a highly active, complicated field of kinematics between galaxies in SQ, and provides evidence for star formation occurring outside galaxies, and some of the first stars to have been born intergalactically.

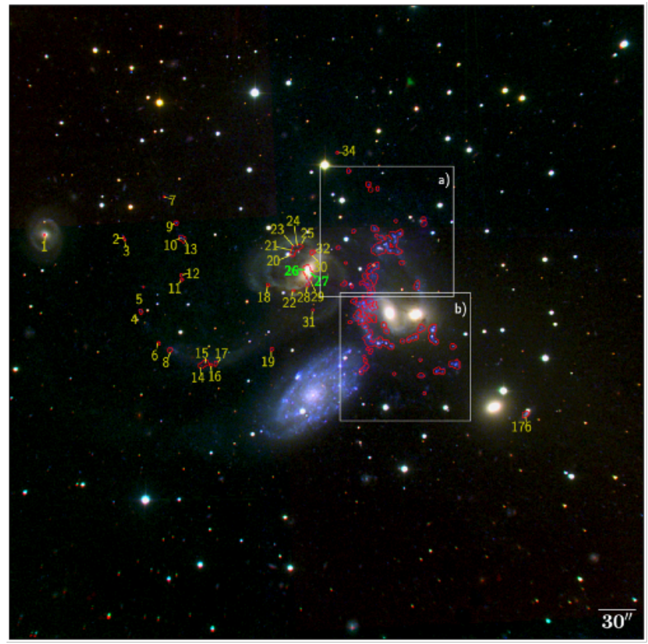


Figure 3: SITELLE image of Stephan's Quintet, showing some of the Hα regions identified in Duarte Puertas et al.'s survey. The bluer, larger is the disconnected NGC 7320, while the two interacting galaxies at the top of box b) are the colliding pair NGC 7318a and 7318b).

From believing that distant galaxies were simply stars themselves, astronomers have come to understand that the medium between galaxies is full of debris from galactic interactions. More careful study of the intergalactic medium in loose clusters like Fornax and Virgo will help us predict the results of our own Milky Way's eventual collision with Andromeda, and closer spectroscopy of the metallicity and radial velocities of intergalactic stars and star-forming regions in compact clusters like Stephan's Quintet will provide insight into the turbulent kinematics of the earliest galaxies after the Big Bang.

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