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The tidal trail of NGC 205?[⋆][†]

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ABSTRACT

Using data taken as part of the Isaac Newton Telescope Wide Field Camera (INT WFC) survey of M31, we have identified an arc-like overdensity of blue, presumably metal-poor, red giant branch stars in the north-west quadrant of M31. This feature is $\sim 1^\circ$ (15 kpc) in extent and has a surface brightness of $\Sigma_{V'} \simeq 28.5 \pm 0.5$ mags arcsec^{-2}. The arc appears to emanate from the dwarf elliptical galaxy NGC 205, and the colour of its red giant branch is significantly different to the M31 disk population but closely resembles that of NGC 205. Further, using data taken with the DEep Imaging Multi-Object Spectrograph (DEIMOS) on Keck II, we identify the radial velocity signature of this arc. Its velocity dispersion is measured to be $\simeq 10\,\mathrm{km\,s^{-1}}$, similar to that of the central regions of NGC 205 and typical of stellar streams. Based upon the spatial coincidence of these objects, the surface brightness, the velocity dispersions and the similarity in colour of the red giant branches, we postulate that the arc is part of a stellar stream, the progenitor of which is NGC 205.

Key words: Local Group - galaxies: general - galaxies: interactions - galaxies: dwarf

1 INTRODUCTION

Over the course of the last decade there has been a lot of renewed interest in the Local Group. This has in part been due to several discoveries of nearby galaxies by various groups (Ibata et al. 1994; Whiting et al. 1997, 1999; Armandroff et al. 1998, 1999; Karachentsev & Karachentseva 1999) that have been made possible because of significant advances in instrumentation. At the same time as these observational discoveries, heirarchical formation scenarios of structure formation, and in particular Cold Dark Matter (CDM), have reached a sufficiently detailed level for the Local Group to begin acting as a laboratory to test and constrain these theoretical models. Here, larger galaxies such as M31 or the Milky Way are postulated to form via the merging of smaller bodies (White & Rees 1978; Searle & Zinn 1978).

The Sagittarius dwarf galaxy, discovered by Ibata et al. (1994), was subsequently shown to have a substantial stellar stream associated with it (eg. Mateo et al. 1998; Majewski et al. 1999; Dohm-Palmer et al. 2001; Ibata et al. 2001), a direct result of its interaction with the gravitational potential of the Milky Way. More recent work has shown that up to 75% of halo M-giants actually belong to the Sagittarius dwarf (Majewski et al. 2003), demonstrating the significant role that this accretion event has had on the make up of our Galaxy. Tidal streams naturally fit in to heirarchical models of structure formation, and evidence for tidal disruption has been found for many of the Galactic dSph satellites (Irwin & Hatzidimitriou 1995) as well as for many galaxies located at higher redshift (eg. Chapman et al. 2003).

The Andromeda Galaxy, M31, provides the only example of a giant spiral galaxy, other than the Milky Way,

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[⋆] Based in part on observations made with the Isaac Newton Telescope on the Island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Institutode Astrofisica de Canarias.

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in which individual stars can be easily resolved using current generations of ground-based technology. As such, we have conducted a large photometric survey of M31 using the INT WFC and the CFH12K camera on the Canada-France-Hawaii Telescope (Ibata et al. 2001; Ferguson et al. 2002; McConnachie et al. 2003; Irwin et al. 2004 *in preparation*, hereafter Papers I, II, III and IV respectively), complete over a total area of 40 $\square^\circ$, ranging out to 80 kpc from the centre of this galaxy (see the figures in Paper IV). Study of the structure of Andromeda is in many ways easier than for our own Galaxy, as our location external to M31 allows us to obtain a global view without the projection problems that plague studies of the structure of the Milky Way.

Initial results of our survey were spectacular, revealing a considerable amount of unexpected substructure. Most significant of all these was the discovery of a giant tidal stream, extending out to some 40 kpc in projection from the centre of M31 (Paper I). A subsequent, deeper survey using the CFH12K camera allowed the three dimensional position of the stream to be calculated, and showed that this feature is over 140 kpc in extent (Paper III). A follow up kinematic survey using the DEIMOS instrument on the KECK II telescope has provided radial velocities for over 800 stars in 13 different fields located at various position in the halo and disk of M31, concentrating on areas of known substructure. Initial results of this survey are detailed in Ibata et al. (2004).

In this *Letter*, we report on the identification of what appears to be another substantial tidal stream in M31, distinct in both colour and kinematics from the M31 stellar stream that has already been reported in Papers I & III. The projected position of this feature, the colour of its red giant branch and its velocity dispersion all suggest that it is tidal debris from M31's bright dwarf elliptical companion, NGC 205. This satellite has long been known to be tidally perturbed by M31 (eg. Hodge 1973; Kent 1987; Bender et al. 1991; Choi et al. 2002; Demers et al. 2003) and the discovery of an associated stream will allow for a better understanding of its evolution. Additionally, if this interpretation is correct, then it is yet more evidence of the ubiquitous nature of streams in galactic halos which, taken with the other substructure present in M31, reveals the complex formation history of this galaxy.

2 PHOTOMETRY

Details of the search strategy, observations and data reduction of our INT WFC survey of M31 can be found in Paper II, and the completed maps showing the global 2D spatial distribution of various stellar populations in M31 can be found in Paper IV. These stellar populations were defined by isolating different locii in the colour magnitude diagrams created from our Johnson V (V′) and Gunn i (i′) photometry (Paper II). In Paper IV, where we show the distribution of "blue" red giant branch stars, a prominence of stars is visible centred at approximately (-0°.6,1°.1). It is this feature that is analysed here in more depth.

The left panel of Figure 1 shows a map of "blue" RGB stars similar to that shown in Paper IV, defined using a sample limited by $20.5 < \mathrm{i}' < 22.5$ mags, $24.85 - 2.85(\mathrm{V}' - \mathrm{i}') < \mathrm{i}' < 26.85 - 2.85(\mathrm{V}' - \mathrm{i}')$. An arc-like overdensity is visible in this figure, with a projected length of $\sim 1^\circ$ (15 kpc), but significantly curved. It extends to the north of NGC 205 but then bends back to the east into the disk of M31. At these galactocentric radii we are unable to follow it further due to the dominant M31 disk population. The morphology of this feature is strongly suggestive of a stellar stream. However, the quantity of substructure in our survey makes it difficult to catagorise these features based on morphology alone; for example it could conceivably also be disrupted M31 outer disk. We estimate the surface brightness of this stellar arc in the V′ band to be $\Sigma_{\mathrm{V}'} \sim 28.5 \pm 0.5$ mags arcsec^{-2}. The Sagittarius stream has a surface brightness of ~ 30 mags arcsec^{-2}, although there is substantial variation with azimuthal angle (Mateo et al. 1998), and the M31 stream reported in Paper I has an estimated surface brightness of $\sim 30 \pm 0.5$ mags arcsec^{-2}. The arc is therefore typically somewhat brighter than these other remnants, althought still well within the expected range for stellar streams.

Figure 2 shows a colour magnitude diagram (CMD) for the arc (left panel), NGC 205 (middle panel) and a typical M31 disk field (right panel). Overlaid are 4 well studied globular cluster fiducial sequences of different metallicities. From left to right, these are NGC 6397 ([Fe/H] $= -1.9$), NGC 1851 ([Fe/H] $= -1.3$), 47 Tuc ([Fe/H] $= -0.7$) and NGC 6553 ([Fe/H] $= -0.2$) (Da Costa & Armandroff 1990; Sagar et al. 1999). Both NGC 205 and the arc show an enhanced bluer red giant branch component relative to the M31 field located at a similar galactocentric radius. Differential reddening is unlikely to account for such a feature. If the stellar arc is somehow related to the outer disk of M31, it is not clear how the colours of the red giant braches could be so markedly different. Comparison of the arc's CMD with the globular cluster tracks shows that it is well described by a mean metallicity of [Fe/H] ~ -0.9. Mould et al. (1984) measured a metallicity for NGC 205, as implied by the colour of it red giant branch, of [Fe/H] $\sim -0.9 \pm 0.2$ (see also Mateo 1998). Our INT phototometry therefore suggests a link between this feature and NGC 205.

3 KINEMATICS

We have used the DEIMOS instrument on Keck II to measure radial velocites of $\simeq 80$ stars per field in a total of 13 fields in various locations across the extent of our photometric survey, selected to lie upon various interesting photometric features. The location of the fields in the outer disk are shown in the right panel of Figure 1. Details of the observations and reduction process, and early results from this survey, can be found in Ibata et al. (2004). The typical uncertainties in the radial velocities that we measure are 5 - 10 kms^{-1}. One of our fields (W91) is centred at an RA and Dec of 0h 41m 5,63s, 42° 34' 25.1". This samples the arc at the point at which it turns to go back into the disk, as indicated in Figure 1. A histogram of the stars in this field with heliocentric radial velocities in the range $-500 \leq v_\odot \leq 80$ km s^{-1}, with a Tonry-Davis coefficent (Tonry & Davis 1979) greater than 7.5 and an average continuum flux in the CaII triplet region > 50 counts per pixel (0.31 Å) is shown in the right hand panel of Figure 3. The left hand panel shows a comparison field (W80) located

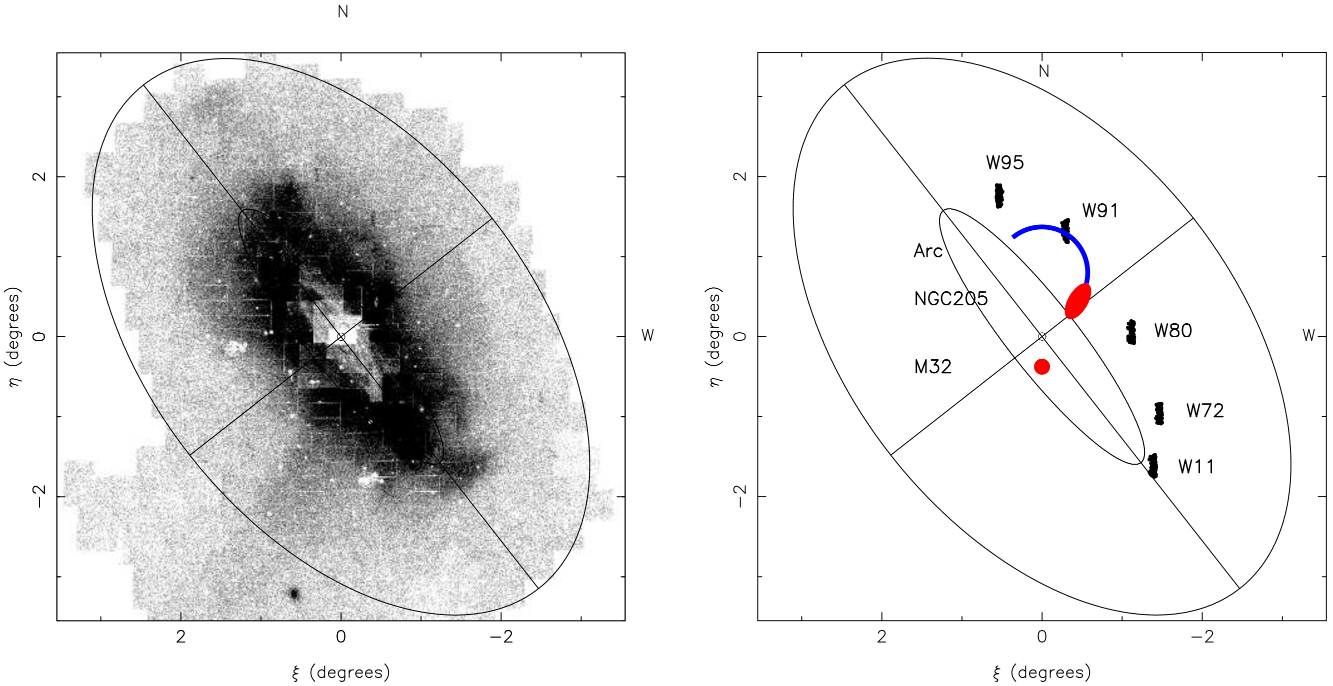

Figure 1. Left panel: the spatial distribution of "bluer" RGB stars, defined by the the colour cut described in the text. This cut is designed to highlight the arc-like density enhancement centred at approximately (-0.°6,1.°1). The dwarf elliptical galaxy NGC 205 is located at (-0.°6,0.°4). The metal poor dwarf spheroidal galaxy And I stands out to the south of the plot, in addition to other complex substructure around the outer SW disk. Right panel: cartoon showing the location of our outer disk DEIMOS fields with respect to M32, NGC 205 and the stellar arc. In both panels, the 2° radius ellipse marks the outer boundary of the optical disk of M31, while the outer ellipse has a semi-major axis $\simeq 55$ kpc and flattening 0.6. This corresponds to the original limit of the INT survey.

at similar galactocentric radius on the other side of the minor axis (Figure 1). For reference, the systemic heliocentric radial velocity of M31 of $v_\odot\,(\mathrm{M31}) \simeq -300$ km s^{-1} (Mateo 1998) is indicated by the dashed line.

In both panels of Figure 3, we can identify various stellar components. The stars with velocities ≥ -100 km s^{-1} are likely foreground stars in the halo and disk of the Milky Way. The stars with $v_\odot < -300$ km s^{-1} are attributable to the halo or bulge of M31, and presumably have an equivalent number with $v_\odot > -300$ km s^{-1}. However, we attribute the peak at -340 km s^{-1} in W80 and the peak at -215 km s^{-1} in W91 to the M31 disk. As both these fields are located approximately symmetrically on either side of M31's minor axis, then we would expect the disk components in each to lie approximately symmetrically on either side of the M31 systemic velocity, as we observe. The solid curves in each panel of Figure 3 are Gaussian fits to the disk component, each with a velocity dispersion of ~ 20 km s^{-1} (uncorrected for measuring errors of typically 5 - 10 km s^{-1}). This value is consistent with our knowledge of the M31 disk. In W91 there is an additional velocity component centred on -160 km s^{-1} with a corrected velocity dispersion of $\simeq 10$ km s^{-1} (dashed curve in Figure 3). As this feature is unique to this field, we attribute it to the photometrically identified stellar arc.

NGC 205 has a measured radial velocity of -240 km s^{-1}. The KECK radial velocity field that we have of the arc is located nearly 1° away from NGC 205, and shows a component centred on -160 km s^{-1} with a corrected velocity dispersion of $\simeq 10$ km s^{-1}. We would expect a substantial velocity difference between NGC 205 and the arc in this field whether the two are related or not as they are seperated by $\gtrsim 15$ kpc, depending upon the inclination of the arc to the line of sight. Therefore, without detailed modelling or stellar velocities in the region between our field and NGC 205, it is impossible to draw any firm conclusions regarding their association based upon only the magnitude of their radial velocities. On the other hand, the velocity dispersion of the arc is typical of stellar streams and is comparable to that which has been measured for the central regions of NGC 205 (~ 14 km s^{-1}; Carter & Sadler 1990; Peterson & Caldwell 1993), which supports a link between the two. We note that the velocity dispersion of NGC 205 is known to show a substantial increase with radius, with a velocity dispersion outside of the nucleus of 40 - 50 km s^{-1} (Bender et al. 1991). This is indicative of tidal disruption and so therefore the presence of a tidal stream would not be surprising.

4 DISCUSSION

The quantity of substructure in M31 makes it difficult to decide upon the origin of any single feature (Figure 1; see also Papers II & IV). Several interpretations as to the origin of this stellar arc are possible, and here we consider each in turn.

One possibility is that this feature is a continuation of the stream reported in Papers I & III. This seems unlikely, however, as the two structures have significantly different colours; the stellar arc is bluer, suggesting a mean [Fe/H] ~ -0.9, while the previously identified stream is red-

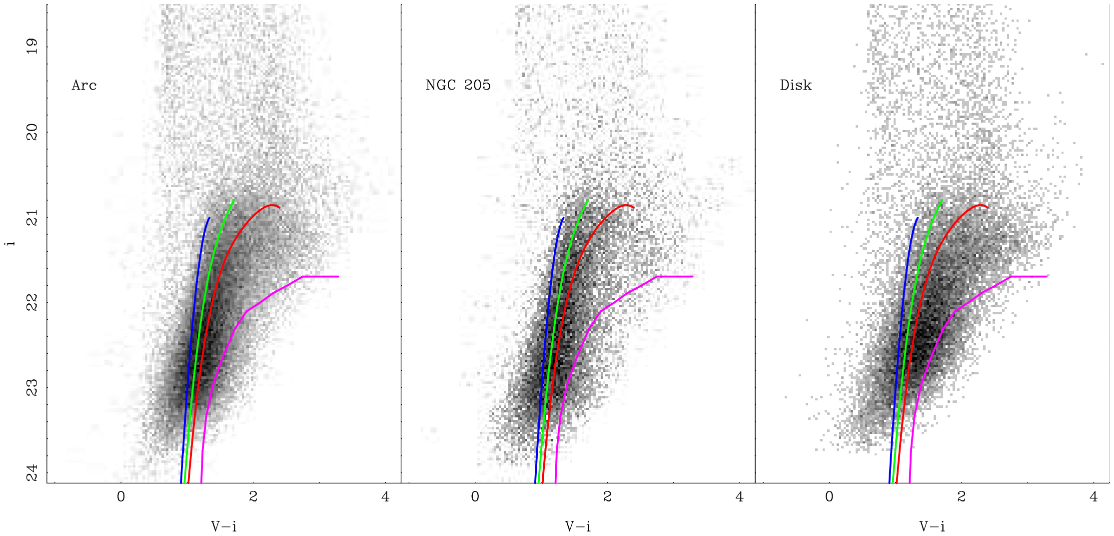

Figure 2. Hess diagrams showing the CMDs for the stellar arc (left panel), NGC 205 (middle panel), and a typical M31 outer disk field (right panel). Overlaid on these are 4 well studied globular clusters sequences of different metallicities. From left to right, these are NGC 6397 ([Fe/H] = −1.9), NGC 1851 ([Fe/H] = −1.3), 47 Tuc ([Fe/H] = −0.7) and NGC 6553 ([Fe/H] = −0.2). Both the arc and NGC 205 have an enhanced bluer red giant branch component compared to to the M31 field, located at a similar galactocentric radius. The enhanced bluer red giant branch in the left hand panel appears to be well represented by a metallicity of [Fe/H] ~ -0.9, in good agreement with that derived for NGC 205 (Mould et al. 1984; Mateo 1998).

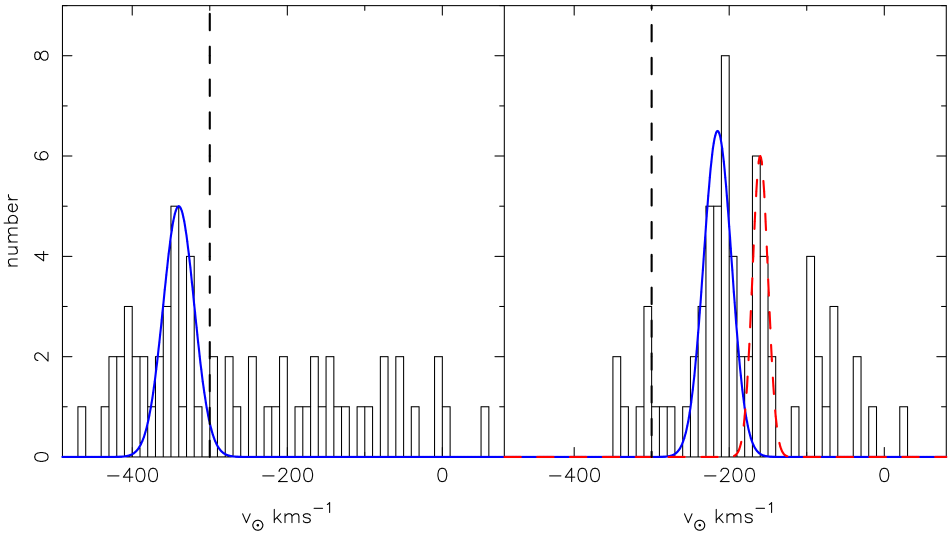

Figure 3. The heliocentric radial velocity distribution in W80 (left panel) and W91 (right panel). The location of these fields is marked on Figure 1. The vertical dashed line in both panels represents the systemic velocity of M31. The solid curves are a Gaussian fit to the M31 disk population, with a dispersion of $\sim 20\,\mathrm{km\,s^{-1}}$. W91 has an additional component present, centred on -160 $\mathrm{km\,s^{-1}}$ with a corrected velocity dispersion of $\simeq 10\,\mathrm{km\,s^{-1}}$, which we attribute to the stellar arc (dashed curve).

der, with a mean [Fe/H] $\sim$ -0.5 (Paper III). Further, the systemic kinematic signatures are quite distinct (Ibata et al. 2004), and so we conclude that the stellar arc is unrelated to the previously identified stellar stream.

A second possibility is that the arc is actually disrupted M31 disk. Although this interpretation is certainly plausible considering the amount of disruption evident in M31 we consider it unlikely, for two reasons. Firstly, as Figure 2 demonstrates, this feature has a substantially different RGB colour to the outer disk, with a significantly enhanced bluer component. We would expect the CMD of any disrupted disk feature to closely resemble the CMD of the undisrupted disk, although this is not the case here. While not disproving a link between the two, it is not clear how this difference can be easily reconciled. Additionally, the velocity dispersion of the arc ($\simeq 10$ $\mathrm{km\,s^{-1}}$) is extremely small for a disk component; we measure a M31 disk radial velocity dispersion of ~ 20 $\mathrm{km\,s^{-1}}$ from Figure 3 and we note that the velocity ellipsoid in the Milky Way disk at the Solar Neighbourhood is $\sim$ 39:23:20 $\mathrm{km\,s^{-1}}$ (Dehnen & Binney 1998). Again, this suggests that this feature is unrelated to the M31 disk.

The third possibility is that this is a stellar stream. Its morphological appearance, surface brightness, and small velocity dispersion are all consistent with this interpretation.

Additionally, the strong spatial coincidence of the "base" of the arc with NGC 205, the close similarity of these objects' red giant branch colours, and the similarity of the arc's velocity dispersion with that for the central region of NGC 205 all allude to this object as the progenitor. As this interpretation is fully consistent with all available photometric and kinematic information, it is our favoured hypothesis. To confirm this, radial velocities in several fields positioned along the arc are required. If correct, then a velocity gradient connecting NGC 205 with the arc in our field will be present. This information will also be vital, should the connection be verified, for dynamical modelling of this intriguing system.

Taking this as our working hypothesis, by counting the excess stars in the on-stream regions compared to off-stream regions, we estimate a stellar luminosity density of $\sim 1\mathrm{L}_\odot$ arcsec^{-2}. If we assume a value for the M/L ratio in NGC 205 of ~ 9 (Held et al. 1990; Carter & Sadler 1990; Bender et al. 1991; Peterson & Caldwell 1993), then the mass density in this stream is of order 9 $\mathrm{M}_\odot$ arcsec^{-2}. We estimate the area of the arc to be $\sim 0.2\Box^\circ$, implying a total mass in the arc of $\sim 1.8 \times 10^7 \mathrm{M}_\odot$, not accounting for projection effects. The mass of NGC 205 is of order $7.4 \times 10^8 \mathrm{M}_\odot$ (Mateo 1998), and so the visible part of the stream contains $\sim 2.5\,\%$ of the mass of NGC 205.

There has been other evidence presented in the literature that suggests NGC 205 is undergoing tidal disruption. Hodge (1973) was the first to undertake detailed photometry of this object and showed that its outer isophotes are twisted, presumable due to tidal interactions with M31. Subsequent photometry was later conducted by Kent (1987), and he found reasonable agreement with Hodge (1973). Most recently, Choi et al. (2002) have found strong evidence for tidal distortion in the isophotes of NGC 205. Figure 9 of Paper II is an isopleth map of M31 from an APM scan of a 75 minute exposure Palomar Schmidt IIIaJ plate taken by Sydney van den Bergh in 1970, and it shows this effect very clearly. The increase in its velocity dispersion as a function of radius, reported by Bender et al. (1991), also suggests that there has been some event which has disturbed the stars in the outer parts of NGC 205 and caused them to have an unusually large velocity dispersion. Recently, Demers et al. (2003) has shown that the number of carbon stars in this galaxy is low for its luminosity, and that there are very few Carbon stars located at greater than $10'$ from the centre, which suggests that NGC 205 has been tidally stripped by M31. Our potential discovery of a tidal stellar stream is therefore unsurprising and is readily testable with further kinematic data. If the stream hypothesis is correct, then the discovery of this stream will greatly aid in the understanding of the evolution of NGC 205 and provide yet further evidence of the prevalence of stellar streams in galactic halos and of the *ongoing* role of accretion events in galactic evolution.

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