CAUGHT IN FORMATION: THE NUCLEAR-CLUSTER-TO-BE IN NGC 2139

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ABSTRACT

Close to its center, the bulgeless galaxy NGC 2139 hosts a star cluster that is younger and less massive than any nuclear star cluster (NC) studied so far. We have measured the Hα velocity field around the photometric center of this galaxy using the VLT ARGUS integral field unit and the GIRAFFE spectrograph in order to constrain different proposed theories of NC formation. We observe that the best-fit kinematic center and the candidate NC appear to be separated by 2.8″ (320 pc). Indeed, the kinematic center is also offset from the galaxy’s photometric center and a possible bar or extended region of star formation in which the young cluster resides, implying that this galaxy is not in dynamic equilibrium. The Hα flux map also reveals other regions of strong star formation in the possible bar. These observations suggest that a nascent NC is forming away from the kinematic center of NGC 2139, which may come to rest there on a timescale of a few 100 Myr.

Subject headings: galaxies: individual (NGC 2139) — galaxies: nuclei — galaxies: star clusters

1. INTRODUCTION

Galaxy centers continue to attract special interest, as they host a number of distinctive phenomena such as active galactic nuclei, central starbursts, and extremely high stellar densities. The last decade has shown that the evolution of galaxies is closely linked to the evolution of their nuclei, as evidenced by a number of relations between global and nuclear properties (e.g., Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Graham et al. 2001; Ferrarese 2002; Haring & Rix 2004).

In view of this general paradigm and as a contribution to the full census of galaxy nuclei over all Hubble types, we are studying the central region of late-type, bulgeless spirals. Prime candidates for the nuclei of bulgeless galaxies have been identified in the form of “nuclear star clusters” (NCs). Such compact, photometrically distinct NCs are found in, or very near, the centers of spirals across all Hubble types (Phillips et al. 1996; Carollo et al. 1998; Böker et al. 1999, 2002; Matthews et al. 1999; Balcéls et al. 2003; Scarlata et al. 2004), as well as in ellipticals (see, e.g., Côté et al. 2006 and references therein).

Due to the lower surface brightness of the background galaxy, NCs in bulgeless galaxies can be studied in more detail than those in earlier Hubble types. It has been shown that NCs in bulgeless galaxies have a number of unusual properties: they are often the most luminous cluster of their host galaxy, and they lie inside the error bars assigned to the location of the photometric center (Böker et al. 2002). Although they are as compact as globular clusters (Böker et al. 2004), they are 1 order of magnitude more massive than the massive end of the Galactic globular cluster mass function (Walcher et al. 2005). They also show evident signs of repetitive star formation (Walcher et al. 2006), which may lead to the formation of disks that are photometrically distinct (bluer) from the underlying NC (Seth et al. 2006). Finally, there are two examples of active galactic nuclei that host NCs: NGC 4395 (Filippenko & Ho 2003) and NGC 1042 (Shields et al. 2008). There is also evidence that the mass of the NC correlates with the mass of its host galaxy (Rossa et al. 2006). NCs are thus prime candidates for representing the unique centers of otherwise bulgeless galaxies.

At least three different scenarios for the formation (and evolution) of NCs can account for most of their properties.

1. NC formation may be a generic property of late-type spirals, if the dynamical center of the galaxy is an a priori well-defined location. This would, e.g., be the natural consequence of a dark matter halo with a cuspy density profile. Magneto-rotational instability could then produce a steady gas inflow onto the galaxy center (Milosavljević 2004). Recently, compression of gas through tidal forces has also been suggested as a possible formation route for NCs (Emsellem & van de Ven 2008). An observational signature of this scenario would be the coincidence of the NC location with the location of the kinematic center, as well as a rather ordered velocity field.

2. On the other hand, NC formation could be a random process. In this picture, any randomly formed, “free-roaming” seed cluster close to the overall center of a bulgeless galaxy would accumulate further gas in the gas-rich central region. The deeper potential well of the cluster would then induce star formation in the accreted gas, thus leading to the very compact, massive objects we observe. The velocity fields would not necessarily be centered on the NC or be well ordered. This scenario would be expected if the central potential of bulgeless galaxies were similar to the constant-density cores advocated by some in the literature (see e.g., de Blok et al. 2003 and references therein).

3. Finally, objects broadly similar to NCs could coalesce through the merging of several young clusters formed close to each other in a starburst event (Oh & Lin 2000; Fellhauer et al. 2002; Capuzzo-Dolcetta & Micocchi 2008).
However, by construction, the distinction between the three formation mechanisms will be blurred with time. In both the second and third formation mechanisms, the formed cluster is drawn to the center of the potential well by dynamical friction. For the case of a deep central potential, the dynamical friction timescale (Chandrasekhar 1943) for a proto-NC can be estimated from equation (3) of Milosavljević (2004), which gives a lower bound for the decay timescale $t_{\text{decay}}$ during which a cluster would sink to the kinematic center of the galaxy:

$$
 t_{\text{decay}} \gtrsim \frac{3 \times 10^7 \text{ yr}}{(50 \text{ km s}^{-1}/100 \text{ pc})^2} \left( \frac{M_\text{cl}}{10^6 M_\odot} \right)^{-1},
$$

where $v_{\text{circ}}$ is the velocity of the cluster on an assumed circular orbit, $r$ is the radius of that orbit, and $M_\text{cl}$ is the mass of the cluster. This decay timescale can be quite short, and afterward all three scenarios follow the same evolutionary path, where a massive preexisting cluster soaks up any infalling gas.

Distinguishing between the three scenarios quoted above is not only central to the identification and formation of NCs, it also helps to inform the debate over the form of the central potential of low surface brightness galaxies (e.g., de Blok 2005; Valenzuela et al. 2007). If scenario 1 could be shown to be valid, this would strongly support the theory predicting diverging mass profiles in bulgeless disk galaxies. Scenarios 2 or 3 would be unlikely if the environment close to the NC were influenced by a steep gravitational potential.

Observational signatures of any of the three NC formation mechanisms described above will most easily be found in galaxies with a young NC. In particular, the velocity field around a NC is interesting, as it allows us to search for a possible offset between the kinematic center and the NC. Such an offset would allow us to clearly distinguish between the different formation scenarios. To maximize the chances of finding a NC offset from the kinematic center, one would ideally target a galaxy whose photometric center was offset from its NC. In NGC 2139, we have a galaxy that meets these criteria: NGC 2139 contains a candidate NC that is somewhat offset from the photometric center and is younger than other NCs. This candidate NC is also less massive than any other NC whose mass has been measured.

After introducing the properties of NGC 2139 and its central cluster, we present the H\textalpha emission-line velocity field of NGC 2139, measured using the ARGUS integral field unit (IFU) of the ESO’s Very Large Telescope (VLT), focusing on the innermost region directly around the potential nucleus of the galaxy. Finally, we evaluate our results both in terms of the NC formation scenarios described above and in terms of the possibility that the central cluster of NGC 2139 is actually a very young super star cluster (SSC) similar to those found in some starburst galaxies, which may over time fade from view and not become a galaxy protonucleus.

2. PREVIOUS OBSERVATIONS OF NGC 2139

NGC 2139 is morphologically classified as an SABcd galaxy (de Vaucouleurs et al. 1991). It is one of the 1000 brightest galaxies in the HIPASS survey (Koribalski et al. 2004), has a recession velocity of 1837 km s\(^{-1}\), and a H I velocity width of $W_50 = 206.7$ km s\(^{-1}\). Based on its velocity width, it is expected to have a maximum, projected rotation velocity of 94 km s\(^{-1}\) (Paturel et al. 2003). However, the H I profile available from the HIPASS archive is quite asymmetric, with the primary peak having a velocity of $\sim$1785 km s\(^{-1}\). A survey of spatially resolved 1.425 GHz emission from IRAS bright galaxies (Condon et al. 1996) indicates that the radio emission from NGC 2139 comes from two components: a primary lobe associated with the main body of the galaxy, and a secondary lobe associated with the plume extending south of the galaxy. The large-scale morphology as seen from publicly available Digitized Sky Survey (DSS)\(^{10}\) images is irregular, showing a few pronounced spiral arms and some tidal features. This, along with many H I region candidates concentrated near the center, is evidence for strong star formation and a possible recent merger event. The Hubble Space Telescope (HST) WFPC2 F814W image (Böker et al. 2002) clearly shows a luminous band (again, presumably star forming) going through the center of the galaxy, indicating a possible bar or star formation filament triggered through gas inflow to the center of the galaxy. This band also includes the luminous star cluster that Böker et al. (2002) classified as a NC.

This central star cluster is unique in several ways. It is the youngest ($4.1 \times 10^7$ yr) star cluster in a sample of nine NCs studied in Walcher et al. (2006; see also Rossa et al. 2006). From an in-depth analysis of its spectrum, these authors find that the spectrum is consistent with the cluster, and does not contain any old stellar population whatsoever. It also is the least massive in the sample of Walcher et al. (2005), with a dynamically determined mass of just $M_\text{cl} = 8.3 \times 10^5 M_\odot$. We note that this star cluster is probably less massive than most NCs, as Rossa et al. (2006) find from a much larger sample with masses derived from stellar population analysis that the inability to spectroscopically infer the populations of faint clusters does introduce a bias toward younger ages, but not necessarily toward higher masses. It is also noteworthy in this context that the effective radius of the NGC 2139 central cluster is 10 pc, making it one of the largest in the Böker et al. (2004) sample.

Indeed, as Walcher et al. (2005) posit, the central cluster in NGC 2139 may be a forming NC, thereby providing an excellent chance to identify an example for scenario 2. Because the fate of the NGC 2139 cluster is still unknown, we will use the term “central cluster” (not NC) for the remainder of this paper, in order to avoid confusion with bona fide NCs that (already) occupy the kinematic centers of their host galaxies.

3. DATA AND REDUCTIONS

Observations of NGC 2139 were carried out with the ARGUS IFU coupled to the GIRAFFE spectrophotograph on the Kueyen telescope of ESO’s Very Large Telescope (VLT) in 2004 May. We used the 0.52\'' lenselet scale size, i.e., a field of view of 11.5\'\'' by 7.3\'\'', and the LR06 grating, which yields a resolution of $R \approx 13,700$, covering a wavelength range 6400 Å $< \lambda < 7100$ Å. The seeing during the observations was reported to be 0.8\''\;0. Because the goal of the observations was simply to study the velocity field, no flux calibration was performed.

Data were overscan- and bias-corrected, and trimmed using the NOAO IRAF\(^{11}\) package ccdproc. Cosmic-ray rejection was performed before spectral extraction using a method described in Andersen et al. (2006). Following cosmic-ray cleaning, basic spectral extraction, flattening, wavelength calibration, and sky

\(^{10}\) The Digitized Sky Surveys were produced at the Space Telescope Science Institute under US Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into their present compressed digital form with the permission of these institutions.

\(^{11}\) IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
This document discusses the analysis of Hα emission lines from NGC 2139, using double-Gaussian fits to model the spectral features. The authors compare single- and double-Gaussian profiles, and discuss the fitting of the data. They find that 88 out of 298 ARGUS spectra show two distinct kinematic components (type 4). The analysis involves using IRAF deHydra for data extraction and IRAF for spectral synthesis.

**4. Analysis**

**4.1. Velocity Field Modeling**

The authors use the centroids of the narrow component A described above as the input to their velocity field modeling. They use a modified Levenberg-Marquardt algorithm to fit a velocity model to the data. The model incorporates two simplifying assumptions: that the rotation of the gas in the disk is circular and that the rotation curve can be approximated by a tanh function. The model is tested on the ARGUS field, and the results show good agreement with the observed data.

The best-fit parameters are determined by minimizing the reduced $\chi^2$ using a tanh function, with the rotation velocity $V_{\text{rot}}$ and scale length $h_{\text{rot}}$ as parameters. The results show that the velocity field of NGC 2139 is consistent with a circular rotation curve, with $V_{\text{rot}}$ and $h_{\text{rot}}$ values of 15 km s$^{-1}$ and 50 km s$^{-1}$, respectively.

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much greater than unity ($\lambda^2 \approx 50$). For any fit where $\lambda^2$ is much greater than unity, there are several possible explanations: (1) the residuals of our velocity field model fit are not Gaussian, (2) the error bars on the line centroids are underestimated, or (3) the model is not a good representation of the data. Indeed, one would not expect our simple model to approximate the true velocity field because the velocity fields of real galaxies can be complicated on fine spatial scales. Since the spectral and spatial resolution of our ARGUS observations is relatively high, it is reasonable to suppose that we are seeing the true complexities of the kinematics at the center of NGC 2139. Presumably, a class of models exists that would better match the data, but that would also become increasingly complex.

Since we are not interested here in modeling the random motions of H II regions or the nonrandom, high-spatial-frequency streaming associated with spiral arms or other similar features, we assume that these variations have a random spatial distribution. We compensate for these contributions by adding a “fuzziness” term to our model. Specifically, we follow the probability theory arguments of Rix et al. (1997) and add an extra error term, $\sigma_{\text{mod}}$, to our models. 

Fig. 2.—Velocities (left), widths (middle), and fluxes (right) of the narrow line profile component (component A). Rotation is clearly apparent in the velocity field, and a simple model fits the velocity measurements adequately. The location of the best-fit kinematic center is marked with a filled circle. The line from the circle marks the direction of the kinematic major axis. Approximately 5° south of the kinematic center is a significant kinematic asymmetry. We find nothing remarkable in the width field—perhaps just a slight broadening of the Hα line roughly coincident with the kinematic center. Two peaks in the flux distribution are clearly visible, but as we show in $\S$ 4.2, neither peak corresponds to the location of either the central cluster or the kinematic asymmetry.

Fig. 3.—Velocities (left), widths (middle), and fluxes (relative to Fig. 2, right) of the second, broader component (component B). No rotation is apparent, and no structure is apparent in either the width or flux fields.
into the $\chi^2$ sum (which we denote as $\chi^2_\nu^2$ to differentiate it from the usual definition of $\chi^2$):

$$
\chi^2_\nu^2 = \sum_i \left( \frac{V_{\text{mod}}^i - V_{\text{obs}}^i}{\sigma_{\text{mod}}^i + \sigma_{\text{obs}}^i} \right)^2,
$$

where $V_{\text{mod}}^i$ is the model velocity at the location of the $i$th spatial element, $V_{\text{obs}}^i$ is the observed velocity of the $i$th spatial element, and $\sigma_{\text{obs}}^i$ is the standard deviation on $V_{\text{obs}}^i$, including both the effects of beam smearing and the centroid measurement error.

Using our model, we were not able to find a unique solution for the disk inclination of NGC 2139, but we were able to find unique solutions by fixing the inclination in the fit. The inclination derived from inverting the Tully-Fischer relation (Rix & Zaritsky 1995) falls between 25° and 40°. Therefore, we fit the velocity field with fixed inclinations varying between 30° and 50°, normalizing the reduced $\chi^2_\nu^2$ to unity (within 1%) by choosing an appropriate value of $\sigma_{\text{mod}}$. We found a major-axis position angle of 150° ± 1°, an observed rotation velocity of $V_{\text{rot}} = 44 \pm 2$ km s$^{-1}$, a heliocentric systemic velocity $V_{\text{sys}} = 1793 \pm 1$ km s$^{-1}$, and a scale length $h_{\text{rot}} = 1.8'' \pm 0.2''$ ($\sim 200 \pm 20$ pc). The error on the kinematic center was just 0.15'' ($\sim 20$ pc). While $\sigma_{\text{mod}}$ systematically varies as a function of inclination, the other kinematic parameters and their associated errors, especially the kinematic center, do not change significantly with respect to the fitting error.

The isovelocity contours are not bent as strongly as in classic disk galaxy “spider diagrams,” as evidenced by Figure 2. While this adds to the uncertainty on the exact location of the kinematic center along the northeast-southwest axis of the galaxy, the spacing between contours (tightly bunched near the best-fit center and more widely spaced further out) implies that the kinematic center robustly lies close to the nominal minor axis (see Fig. 4).

The kinematic center is offset with respect to the peaks in Hα flux and, as we shall see in § 4.2, from the central cluster as well. The high-precision method with which we determine the kinematic center from our velocity field fitting does not include possible sources of systemic uncertainty. First, we chose one of the two separate Hα components, each at a different velocity, without being able to unambiguously identify a physical reason to do so. Second, when we use only this one component in our velocity field modeling, there is a kinematic asymmetry 5° along the major axis that is not understood (Fig. 2 and § 4.2). If this were taken as an indication that the velocity field is not well ordered, it could be used to argue against the NC formation mechanism that requires the center to be a special place in these late-type galaxies.

On the other hand, the center we find is quite robust. Leaving out some of the more questionable data, removing the kinematically asymmetric data, and trying to force the code to produce a center at a different location by varying the initial fit parameters all fail to produce a significant shift in the model’s kinematic center; none of the kinematic parameters changes more than the errors quoted above. So, assuming a simple rotation curve and velocity field model, we find that the best-fit kinematic center is well constrained, which implies a single strong minimum in $\chi^2$ space. Figure 4 shows the derived rotation velocities against de-projected azimuthal angle and radius. We recover the expected sinusoidal shape and “s” shape, respectively, indicating that our simple model for the velocity field does an adequate job of describing the data. Forcing the kinematic center away from the best-fit location would significantly alter the shape of these plots.

Further supporting evidence for the accuracy and interpretation of the ARGUS velocity field comes from the H i recession velocity. At first glance, the kinematic parameters derived from the Hα velocity field do not agree with the H i observations. In particular, the Hα-derived systemic velocity ($1793 \pm 1$ km s$^{-1}$) is much smaller than the 1837 km s$^{-1}$ found from HIPASS. While global line profile asymmetries can create differences between H i single-dish recession velocities and the systemic velocities derived from velocity fields (Andersen & Bershady 2007), the sense of the discrepancy is reversed. The true systemic velocity, based on the asymmetry of the H i profile, should be even higher than 1837 km s$^{-1}$. However, as mentioned in § 2, the Condon et al. (1996) radio continuum maps suggest that there are two discrete sources of radio emission from NGC 2139. If the stronger peak in the H i profile corresponds to the larger source of radio continuum emission associated with the main body of NGC 2139, then we find good agreement between this peak velocity ($\sim 1795$ km s$^{-1}$) and our result. Furthermore, if the H i emission is coming from two distinct sources at two distinct velocities, then our measured rotation velocity will account for almost the whole width of the primary peak. Even if this “two gas clouds” picture is not correct, we are observing a sizable amount of the total rotation in NGC 2139 (44 km s$^{-1}$ from our Hα velocity field versus 94 km s$^{-1}$ from the double-peaked H i profile) in a very small area near the center of the galaxy, lending credence to our interpretation that the kinematic center lies in the ARGUS field of view.

Finally, the velocity field possibly indicates that the luminous band described in § 2 may be a star formation filament rather than a stellar bar because, as we show in the next section, the star formation knots are indeed located in this band, but the velocity field is not distorted by this feature. The kinematic center of NGC 2139 is well separated from this band, and while bars are observed offset from galaxy centers in late-type galaxies such as the LMC (de Vaucouleurs & Freeman 1972), this behavior is often attributed to tidal forces (e.g., between the Milky Way and the LMC; van der Marel et al. 2002). Observations provide some evidence that NGC 2139 is affected by tidal forces, but whether the possible tidal effects are quantitatively sufficient to explain the offset we see between the stellar and gas kinematics is beyond the scope of this paper. Although we note that the distortions we observe in the velocity field seem unlike those expected from a bar (Roberts et al. 1979), a separate study would be needed to convincingly argue against the presence of such a bar.

### 4.2. IFU Continuum to HST Image Registration

Before we can compare our best-fit kinematic center to the location of the central cluster in NGC 2139, we need to register the
**HST** WFPC2 F814W image of Böker et al. (2002) to the continuum flux from the ARGUS IFU. We first measured continuum levels from the IFU data within a 400 Å spectral window between 6600 Å < λ < 7000 Å, in which emission lines were masked.

We registered this continuum IFU image to the HST image by first smoothing the **HST** image with a 0.8″ Gaussian to roughly match the seeing during our ARGUS observations. Then, for a given position of the IFU with respect to the smoothed image, we extracted the flux within the footprint of each IFU spaxel. We fit a linear relation between the IFU and the **HST** spaxel fluxes and tabulated \( \chi^2 \). We mapped \( \chi^2 \) over a grid in north-south and east-west offsets of the IFU with respect to the **HST** image, and found a very good fit between the **HST** extracted fluxes and the IFU continuum fluxes. We used our \( \chi^2 \) map to generate errors on our image to IFU registration (Fig. 5).

With the IFU registered to the **HST** image, we were able to assign coordinates to the best-fit kinematic center. This kinematic center is located at R.A. = 06h01m07.98s and decl. = -23°40’19.3″ (J2000.0), with errors of \( \pm 0.2″ \) on each axis (based on both registration errors and the formal velocity field errors). This is 2.8″ away from the location of the central cluster at R.A. = 06h01m07.88s and decl. = -23°40’21.7″ (Fig. 6). Here and below, all right ascension and declination values refer to the J2000.0 coordinate system of the WFPC2 F814W **HST** image, which has an absolute accuracy with respect to the ICRS system of \( \pm 1″ \).

We note that the central cluster is coincident with a region poorly fit by the global velocity field (Fig. 6), although the largest deviation from the velocity field does not correspond to any feature in the image. We also find that the central cluster is located near, but is not coincident with, the two peaks in \( H\alpha \) flux. The central cluster is separated by 3.2″ from the brightest source of \( H\alpha \) emission. This brighter, primary peak of \( H\alpha \) emission has no clearly identifiable counterpart in the **HST** F-band image. We postulate that the primary peak in \( H\alpha \) emission represents an even younger SSC, perhaps still enshrouded in its birth cloud. Perhaps future mid-infrared observations will reveal structures coincident with the large deviation from the velocity field southwest of the central cluster, and the bright peak in \( H\alpha \) emission to the west of it.

### 4.3. Determination of the Photometric Center

Finally, we re-determine the location of the photometric center of NGC 2139 from the **HST** WFPC2 F814W image. This exercise was carried out in Böker et al. (2002) with the aim of deriving photometric centers for a large number of galaxies in a homogeneous way. Here, we focus on understanding one special case. Indeed, NGC 2139 has a rather irregular appearance on the PC chip. In particular, the luminous band going through the center of the object has a number of secondary brightness peaks (secondary to the central cluster), which shift the photocenter each time the radius of the isophotal ellipse becomes large enough to include one more of these peaks. We have therefore convolved the image with a \( \sigma = 10″ \) Gaussian before using the exact same setup as Böker et al. (2002). We now define the isophotal center to be the arithmetic mean of all ellipse centers between radii of 0.7″ and 18.4″. We thus obtain the following photocenter: R.A. = 06h01m07.95s ± 0.09s and decl. = -23°40’21.6″ ± 0.4″. The photometric center is 2.3″ ± 1.4″ away from the kinematic center and 1.0″ ± 1.4″ away from the central cluster. We note that this result still depends strongly on the range of radii used to determine the photometric center. The location of the photometric center is shown in Figure 6.

### 5. Nuclear Cluster or Young Super Star Cluster?

We have provided new data to judge whether the classification of the central star cluster in NGC 2139 as a NC is correct. While all the results we have obtained from the \( H\alpha \) velocity field are consistent with the interpretation of the cluster being a nascent NC, we examine here the possibility that this cluster is not a NC and instead is a more normal young SSC. This possibility is supported by the emission-line profiles as observed in the VLT UVES data published in Walcher et al. (2005, 2006). Figure 7 shows the \([S\,ii]\) doublet emission lines in three apertures along the spatial direction. It is clear that the lines are broadest at the location of the central cluster. The FWHM for this aperture, as determined from a single-Gaussian fit, is 2.3 Å = 100 km s\(^{-1}\). However, the lines have two separate kinematic components, which is consistent with the ARGUS \( H\alpha \) data. These two components can be fit by two Gaussians, but high-velocity wings remain that are not fit even by this double-Gaussian fit. These wings have a full width at zero intensity of 300 km s\(^{-1}\). The redder peak is coincident in velocity with the cluster stars (measured \[12\] The photometric center as determined from the DSS image of NGC 2139 was statistically equivalent.
from the Ca Triplet), while the bluer peak is separated by approximately 55 km s^{-1}. One could speculate that we are seeing a superbubble around the cluster, where the part that is coming toward us is visible, while the receding part of the bubble is hidden by extinction inside the cluster itself. Such complex emission lines with two components are routinely seen in H II regions and very young clusters (e.g., Vanzi et al. 2006; Henry et al. 2007).

The stellar velocity dispersion for the cluster in NGC 2139 is $\sigma_v = 16.5 \pm 1$ km s^{-1} (Walcher et al. 2005), so its escape velocity is approximately $\sqrt{2}\sigma_v \approx 23$ km s^{-1}. This means that the gas in the peak coincident with the cluster is marginally bound ($\sigma_{\text{gas}} = 20$ km s^{-1}). However, neither the high-velocity wings nor the gas moving toward us are bound to the central cluster.

These properties can be compared to the discussion in Gilbert & Graham (2007). These authors publish emission-line widths...
for a large sample of SSCs in the Antennae. The velocities in the NGC 2139 cluster are consistent with, yet at the high end of, those observed by Gilbert & Graham (2007). As these authors show, such high velocities and complex line profiles are associated with winds and mass loss from very young star clusters, the so-called SSCs. Naturally, star formation and winds could also be associated with a NC undergoing a rejuvenation burst.

We also remind the reader that the effective radius of the NGC 2139 cluster is 10 pc and is one of the largest in the Bo"eker et al. (2004) sample. This could be interpreted in the context of the study of Mengel et al. (2005), who show that the radii of SSCs are linked to their age. These authors show that the effective radii of typical SSCs are 16 \pm 15 pc for 4 Myr old clusters and 6.5 \pm 5.3 pc for 8–11 Myr old clusters. In Gilbert & Graham (2007), these large radii are interpreted as expansion following mass loss through winds. Of course, a similar effect could puff up the radius of young NCs compared to their older cousins.

The environment around the central star cluster also suggests that this may be one of multiple SSCs in NGC 2139. The multiple sources of radio continuum emission, the luminous band in which the central star cluster is located, the larger scale tidal features, and the multicomponent H_\alpha and [S \\ II] emission are all consistent with a recent merger event, which may drive gas to the center and initiate the formation of SSCs. Indeed, the two bright H_\alpha sources in the vicinity of the central star cluster may be very young SSCs.

While the above arguments lead to a certain degree of uncertainty with regard to the classification of the central cluster in NGC 2139, we can predict whether we would identify the cluster as a NC 3 Gyr from now. Using a mass-to-light ratio \( M/L_I = 0.87 \), as predicted by Bruzual & Charlot (2003) for a 3 Gyr old stellar population and using a cluster mass of \( 8 \times 10^5 M_\odot \), we obtain \( L \approx 7 \times 10^5 L_\odot \) after 3 Gyr. This is significantly brighter than the cutoff luminosity of a NC as observed in Bo"eker et al. (2002).

If the identified central star cluster can somehow merge with other nearby clusters (such as those associated with the two bright peaks of star formation in the H_\alpha map) and fall to the kinematic center, then the resultant NC could be even brighter. If this were to happen, it would support the NC formation scenario whereby multiple stellar clusters coalesce to form the final NC (Fellhauer et al. 2002). That so many young clusters are present near the center of NGC 2139 is another indication that the galaxy recently experienced a tidal interaction capable of forming clusters (Bekki et al. 2004).

We now assess the probability that such a massive and luminous cluster would form by chance in a late-type disk galaxy such as NGC 2139. To that end, we compute the star formation rate (SFR) necessary to produce a cluster of mass similar to the central cluster in NGC 2139. Due to size-of-sample effect, the maximum mass \( M_{\text{max}} \) of a star cluster scales with the total number \( N \) of star clusters formed, or equivalently with the star formation rate (see Larsen 2002). The central cluster in NGC 2139 has an absolute \( I \)-band magnitude of \( M_I = -12.65 \) (Bo"eker et al. 2002), and from its age and Bruzual & Charlot (2003), we infer a color \( V - I = 0.5 \). Following the relations given in Weidner et al. (2004), we infer that a total SFR of roughly 1 \( M_\odot \text{yr}^{-1} \) is needed to form one such cluster. Emission-line fluxes for NGC 2139 are given in Moustakas & Kennicutt (2006) for a nuclear aperture

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\frac{\lambda (\text{Å})}{R (\text{Å})}
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Fig. 7.— Top: Spatial profiles of the [S \\ II] emission lines measured from VLT UVES high-resolution spectra \((R \approx 30,000)\) in three apertures of \( 1'' \times 1'' \). The middle aperture includes the central cluster itself, and apertures \( 2'' \) on either side are also shown. Bottom: HST WFPC2 F814W image centered on the central star cluster of NGC 2139, with the UVES slit overlayed. The broad emission lines in general and the double-peaked emission line on the central cluster in particular are compatible with a very young massive star cluster (SSC) in an active star-forming region.
of 2.5" × 2.5", and for the total galaxy (120" × 120""). The Hα fluxes are $(23.11 \pm 0.97) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ and $(3310 \pm 130) \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$, respectively. Using a distance of 23.6 Mpc (Böker et al. 2002) and the standard Kennicutt (1998) conversion of SFR ($M_\odot$ yr$^{-1}$) = $7.9 \times 10^{-42} L_{H\alpha}$ (erg s$^{-1}$), we obtain nuclear and total SFRs of 0.01 and 1.7 $M_\odot$ yr$^{-1}$, respectively. The central cluster is the brightest cluster in the area of the PC chip, which is 36" × 36" (4 kpc × 4 kpc). However, the surface brightness of the galaxy falls rapidly outside of the chip, so it is likely that most of the Hα flux observed by Moustakas & Kennicutt (2006) stems from the area actually observed. In summary, it is likely that a cluster similar to the one observed in NGC 2139 forms somewhere in the disk of the galaxy. The likelihood that this happened by chance in the central 2.5" × 2.5", however, remains low. Note, however, that with the 40 km s$^{-1}$ current rotational speed of the galaxy and the estimated cluster age, the cluster could have moved by as much as 1.5 kpc since formation. As the cluster seems to have formed from disk material and is still associated with the gas overdensity in which it formed, it is not likely, however, that the cluster has a large peculiar motion with respect to the rest of the galaxy disk. Whether special conditions close to the center of the galaxy need to be invoked thus remains open.

6. SUMMARY

We have presented VLT ARGUS IFU data to ascertain whether the location of the kinematic center of the late-type galaxy NGC 2139 and the location of its central cluster, previously classified as a NC, coincide spatially. We have analyzed the velocity field in the ARGUS field of view and found the kinematic center to be at R.A. = 06:01:07.98 and decl. = −23°40′19.3″, with errors of ±0.2″ on each axis. The location of the central cluster is at R.A. = 06:01:07.88 and decl. = −23°40′21.7″, 2.8″ offset from the kinematic center. The photometric center is at R.A. = 06:01:07.95 ± 0.09″ and decl. = −23°40′21.6″ ± 0.4″, and is 2.3″ ± 1.4″ away from the kinematic center and 1.0″ ± 1.4″ away from the central cluster. While some caveats remain concerning our quoted precision for the location of the kinematic center, it appears unlikely that the location of the NC 2139 central star cluster is coincident with the kinematic center.

Based on the peculiar Hα and [S ii] emission from the core of NGC 2139, we conclude that the central cluster is actively forming stars. While the properties of the central cluster in NGC 2139 are thus compatible with those of a SSC, we have presented several arguments why it can nonetheless be considered to be a NC progenitor object:

1. Based on the projected luminosity of the cluster in 3 Gyr, we predict that it would be classified as a NC according to the criteria of Böker et al. (2002) if it has not lost a significant fraction of its mass to evaporation.
2. Other young star clusters associated with peaks in the Hα distribution may merge with the visible one to produce a multi-aged, very luminous NC. Alternatively, more gas from the luminous band may fall into the central star cluster and form stars in situ.
3. While the NGC 2139 central cluster is not currently at the center, the relatively well-ordered velocity field means that the cluster should fall to the center within a relatively short period of time: if the cluster is 320 pc (2.8″) away from the kinematic center with a rotation velocity of 15 km s$^{-1}$, equation (1) yields a derived dynamical friction timescale of 110 Myr, which is comfortably longer than the 41 Myr derived by Walcher et al. (2006). It should be noted, however, that this is only an order of magnitude estimation, as it will depend on the exact form of the gravitational potential. In the case considered by Milosavljević (2004), the value we derive is a lower bound. On the other hand, if NGC 2139 is undergoing a dissipative tidal interaction, as the images and radio data seem to indicate, then the dynamical friction timescale for the central star cluster could be significantly shorter (e.g., Peñarrubia et al. 2004; Capuzzo-Dolcetta & Vicari 2005; Miocchi et al. 2006; Fujii et al. 2008). Regardless, it appears that within a relatively short time, this cluster may take up residence at the nucleus of NGC 2139.

Although we caution that NGC 2139 is in many ways an unusual object among all late-type spirals containing NCs, we can attempt to view our results in terms of the three scenarios described in § 1. We find a confusing picture: the properties of the central cluster in NGC 2139 are compatible with the free-roaming seed cluster formation described by scenario 2. However, we observe clear rotation of the galaxy, which is as predicted by scenario 1. Finally, a second cluster seems to be forming close to the visible central cluster, suggesting that for NCs the merger mechanism described in scenario 3 can also play a role.

In summary, it appears that seed NCs have formed in NGC 2139, fed by an inflow of gas, possibly due to a recent merger event. It is clear that larger data sets will be needed to clarify whether NCs in general are true galaxy nuclei. IFUs with larger fields of view would help in this endeavor, particularly if the central velocity fields are more disordered than that observed in NGC 2139. The field would also benefit enormously from targeted simulations assessing the viability of the three formation scenarios in relation to all the observed properties of NCs.

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