THE ASTROPHYSICAL JOURNAL, 353: L7–L10, 1990 April 10


# DISCOVERY OF A MASSIVE, YOUNG STAR CLUSTER IN THE FILAMENTS OF NGC 1275

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*Received 1989 December 11; accepted 1990 January 31*

## ABSTRACT

Optical and near-UV spectroscopy of an emission-line filament in the low-velocity system of NGC 1275 has revealed the presence of a young star-forming region, as evidenced by a very blue continuum source coincident with line emission characteristic of H II regions. This is the first direct detection of star formation in gas thought to be part of a cooling flow. If this young cluster is representative of star formation in cooling-flow galaxies, the current initial mass function (IMF) for these objects is *not* truncated at a level that excludes the formation of massive stars. For a Salpeter IMF, the cluster contains a mass similar to the largest globular clusters associated with the Milky Way ($\sim 5 \times 10^6\ M_\odot$). A dynamical constraint on the total mass of the stellar cluster may be available through measurement of its emission-line widths. We suggest that the A-star continuum characterizing the near-nuclear population of NGC 1275 is better explained as the signature of a fading starburst, rather than as star formation in a cooling flow.

*Subject headings:* galaxies: clustering — galaxies: intergalactic medium — galaxies: stellar content — stars: formation

## I. INTRODUCTION

X-ray observations of clusters of galaxies have revealed associated coronae of keV gas with inferred central cooling times of less than a Hubble time (see, for example, the review by Sarazin 1988). This fact has led to models for steady state accretion, or cooling flows, of intracluster gas that may consist of more than 400 $M_\odot$ yr$^{-1}$ in some objects (Fabian *et al.* 1985; scaled to $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, which is used throughout this *Letter*). Optical observations of the same objects are generally inconsistent with star formation rates of this magnitude for standard stellar initial mass functions (IMFs) (McNamara and O'Connell 1989). The central galaxy in the Perseus cluster, NGC 1275, displays such an inconsistency; its mass accretion rate, $\dot{M}$, inferred from X-ray imaging is $\sim 130\ M_\odot$ yr$^{-1}$ (Fabian *et al.* 1981), while normal IMF star formation is inferred from its optical spectral energy distribution to be no more than $\sim 10\%$ of this figure (e.g., Romanishin 1987).

This discrepancy has led to suggestions that the IMF is skewed to primarily low-mass star formation in the cooling gas. Scenarios in this vein rely on the conjecture that a Jeans mass in the high-pressure cooling flow environment would be relatively small and might serve as a typical mass scale for star formation (e.g., Fabian, Nulsen, and Canizares 1982). However, plausibility arguments of this nature are open to serious objections (Silk *et al.* 1986).

Here we report the discovery of a region of recent star formation in the filaments of the cooling-flow galaxy NGC 1275 ($cz \approx 5200$ km s$^{-1}$). This region shows blue continuum radiation and nebular emission lines that can be attributed to O-type stars and their associated Strömgren spheres. In contrast to other evidence for hot stars in cooling-flow galaxies (e.g., McNamara and O'Connell 1989), our observations directly show stars forming in the nebular condensations often regarded as cooling-flow products. If this region is typical of star formation in cooling flows, the IMF is clearly *not* truncated at a low upper-mass cutoff in these objects. This discovery provides additional evidence in support of modified cooling flow scenarios with significantly lower mass accretion rates than are inferred from models that neglect heating sources for the intracluster gas.

## II. OBSERVATIONS

Spectra of NGC 1275 covering 3400–6940 Å were obtained in 1989 September and October with the 3 m Shane reflector at Lick Observatory. Observations were acquired through a 2″.5 wide slit centered on the galaxy nucleus and oriented at position angle (PA) 62°. Spectral resolution for these data is approximately 3.5 Å redward of 6140 Å, and 7 Å elsewhere. Atmospheric seeing was typically 2″. The two-dimensional spectra and one-dimensional extractions were reduced and calibrated using standard techniques. These observations were obtained as part of a larger program to study the ionization properties of the filaments of NGC 1275, results of which will be presented elsewhere.

The slit admitted light from a filament of emission-line gas that extends approximately radially in projection for at least 9″ (3 kpc) at a similar PA ($\sim 62°$, i.e., east-northeast from the nucleus; see Figs. 1*a* and 1*b* [Pl. L2]). Inspection of this filament's emission-line spectrum reveals that the ionization state of the emitting material varies markedly as a function of position. In particular, the outer portion of the filament shows strong low-ionization lines typical of nebulosity in cooling-flow galaxies (Heckman *et al.* 1989), with line intensity ratios similar to those predicted for shocked gas (Shull and McKee 1979); prominent [O I] $\lambda\lambda$6300, 6363 and [N I] $\lambda$5200 are especially noteworthy in this regard. At smaller distances from the nucleus, however, the nebulosity shows quite different line ratios indicative of a higher ionization state. Figure 2*a* shows the low-ionization emission present in a 3″.3 extraction centered 24″ (8.1 kpc) from the galaxy nucleus. An extraction of the same width and centered 18″.5 (6.2 kpc) from the nucleus is shown in Figure 2*b*.

We note specifically the Balmer lines and [O III] $\lambda\lambda$4959, 5007, which are greater in absolute flux in the inner extraction. Compared with emission from low-ionization species such as

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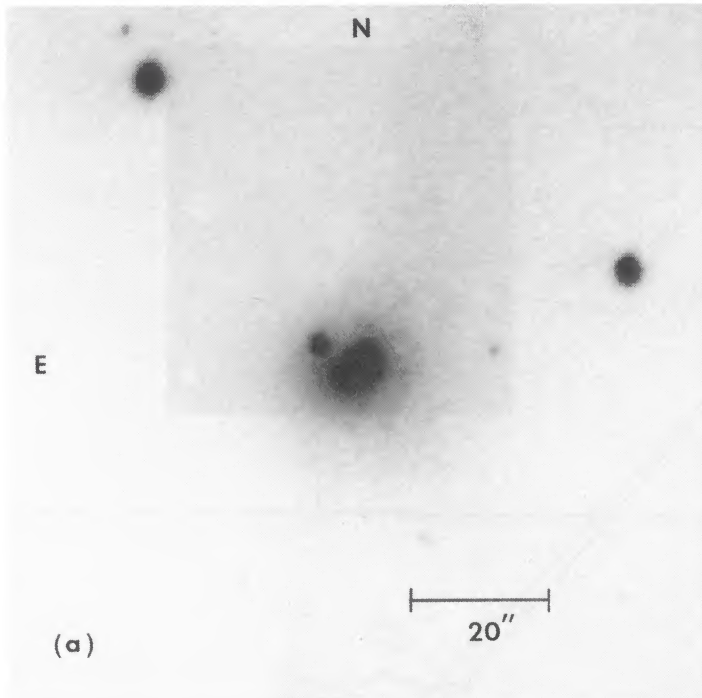


FIG. 1*a*

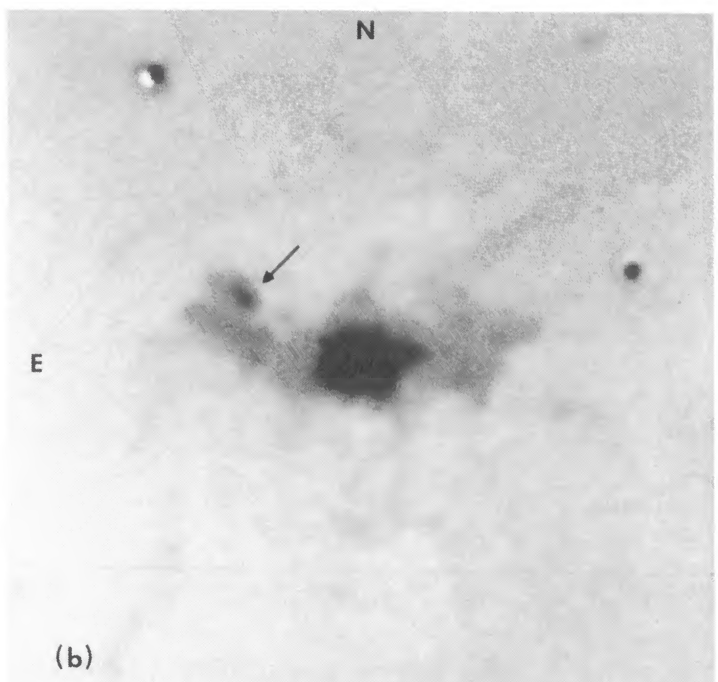


FIG. 1*b*

FIG. 1.—(*a*) Narrow-band CCD image of NGC 1275 showing continuum emission. The observation was obtained through a filter of width 75 Å centered at 6563 Å. The broad vertical feature intersecting the west side of the galaxy is an artifact caused by a bright star outside of this field. (*b*) Narrow-band CCD image of NGC 1275 showing continuum-subtracted Hα + [N II] emission from the low-velocity system. The young star cluster is indicated by the arrow. The emission-line observation was obtained through a filter of width 76 Å centered at 6693 Å; the image in (*a*) was used for subtraction of continuum light. Imperfectly subtracted stellar images are visible north of the galaxy. Both images were acquired with the 1 m Nickel reflector at Lick Observatory.

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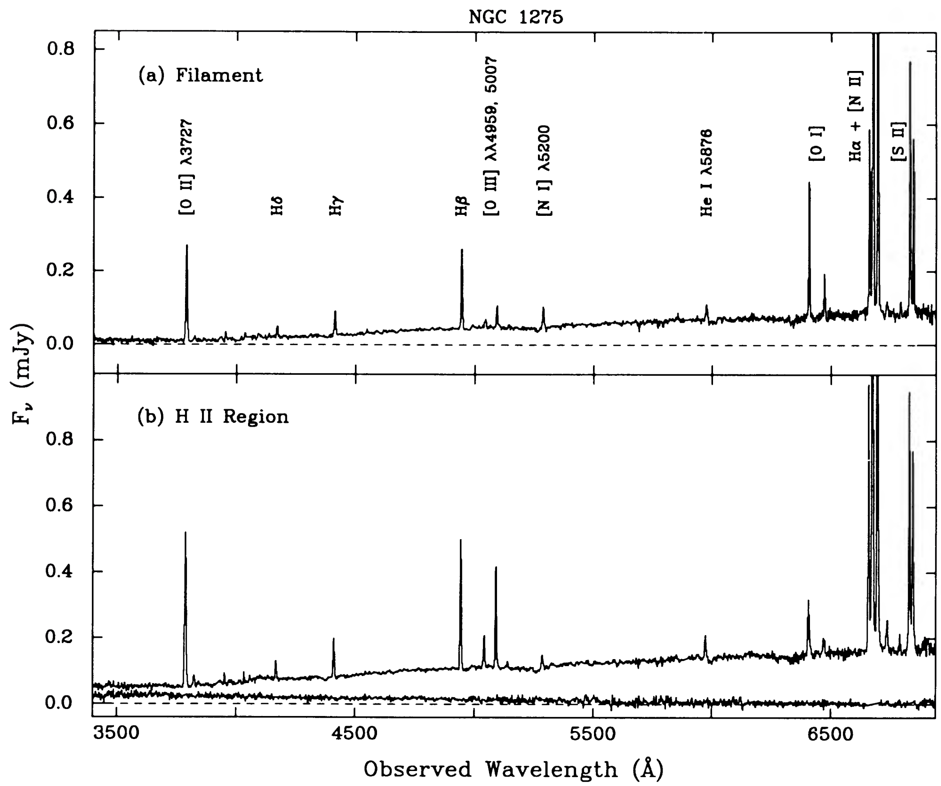


FIG. 2.—(*a*) Spectrum of NGC 1275 from a region of size 3″.3 × 2″.5, located 24″ from the nucleus at PA 62°, showing strong low-ionization emission lines characteristic of the filaments in this galaxy. The observed intensity ratio of [N II] λ6583/Hα in this spectrum is 0.76. Weak emission from the high-velocity system ($cz \approx 8200$ km s$^{-1}$) is evident in this figure and in (*b*) especially [O II] λ3727, [O III] λ5007, and Hα. (*b*) Spectrum from a region of size 3″.3 × 2″.5, located 18″.5 from the nucleus at PA 62°, showing relatively strong emission lines characteristic of H II regions. The observed intensity ratio of [N II] λ6583/Hα in this spectrum is 0.65. The lower spectrum shows the blue continuum in a 4″.6 × 2″.5 synthetic aperture at the same position, after subtraction of continuum light from the old population in NGC 1275. Residual emission features have been removed through interpolation.

[N I] and [O I], these lines are also considerably greater in *relative* strength in the inner aperture. The intensity ratio [O III]/Hβ is also much larger in this region. Significantly, emission from hydrogen, $O^{++}$, and other ionized species peaks at a location coincident with a faint and extremely blue continuum source. Night-sky emission was subtracted from the emission-line spectra in Figures 2*a* and 2*b* using a fit to background regions located far from the galaxy center and devoid of nebular emission. The continua in these spectra are thus dominated by starlight from the relatively old population of the underlying galaxy. The spectrum of the blue continuum source, which was spatially unresolved, was obtained by repeating the inner extraction using a width of 4″.6 and a fit to background adjacent to the extracted swath; this process removed contributions from the night sky and also from the underlying old population. The result is shown at the bottom of Figure 2*b* and appears as a blue, featureless continuum with an almost linear spectral energy distribution.

The spatial coincidence of the blue continuum and relatively high ionization nebular emission strongly suggests that we have detected a young cluster of stars and associated H II regions. Ratios of emission-line strengths for this region are in most cases intermediate to values characteristic of H II regions and shocked gas (Shields and Filippenko 1990). This may indicate that within our synthetic aperture we have observed a projected combination of H II regions and normal filament material, or perhaps shocked gas associated with the recent star formation. The inner, H II region emission and the low-ionization nebulae observed elsewhere in the filament differ in velocity by $\lesssim 100$ km s$^{-1}$, and both components are at a redshift ($\sim 5100$ km s$^{-1}$) indicative of association with the low-velocity system of NGC 1275. Comparison of optical images with radio maps of NGC 1275 reveals no apparent special relationship between this filament and the radio source structure. We also point out that the region we identify here as a young cluster is *not* to be confused with an unresolved source located $\sim 7''$ from the galaxy nucleus at a similar PA; the latter object has been suggested as a region of star formation or other energetic activity (Metik and Pronik 1984), but our data confirm previous observations indicating that it is a Galactic foreground star (e.g., Minkowski 1968) of spectral type F.

## III. CHARACTERISTICS OF THE CLUSTER

The discovery of a young stellar cluster in the filaments of NGC 1275 is significant as the first unambiguous detection of star formation in material that probably originated in a cooling flow. Evidence for association of the cluster with the filament is strong, based on the projected morphology of the nebulosity and on the agreement in redshift discussed above. We also note that the surface brightness of this filament drops significantly at projected locations interior to the cluster position, so that the star formation appears to occur at the inner edge of the filament. This detail is consistent with stars forming out of the filament gas. Buoyancy effects in the quasi-hydrostatic flow will cause aggregates of cooling gas to elongate into radial filaments, with the densest components sinking to the smallest radii; the densest clouds are also expected to be the most efficient at cooling and collapse leading to star formation.

To characterize the dominant stellar contributors to the observed continuum, we synthesized intrinsic *UBV* magnitudes after removing the contribution of emission lines. Reddening corresponding to $A_V = 0.54$ mag in Galactic foreground extinction (Burstein and Heiles 1984) and intrinsic $A_V = 0.80$ mag (estimated from the observed ratios of hydrogen recombination lines) was removed using the mean extinction curve of Cardelli, Clayton, and Mathis (1989) in the appropriate velocity frames. Estimates of $U$ are particularly uncertain since our spectrum only extends to ~3340 Å in the rest frame of NGC 1275. The results yield $V = 19.9$, $U-B = -1.4$, and $B-V = -0.9$. These colors are inconsistent with any population of known hot stars in the sense of being excessively blue (Massey 1985), and we attribute this inconsistency to errors in subtraction of the background galaxy light that dominates the surface brightness at the position of the young cluster. Absorption underlying the Balmer lines could in principle have caused us to overestimate the intrinsic $A_V$ and hence the reddening correction for this source. However, the absence of Balmer continuum absorption suggests that the continuum originates largely in hot, O-type stars with presumably only weak Balmer-line absorption.

Despite uncertainties in the overall continuum shape for the stellar cluster, its spectral energy distribution is clearly very blue compared with the average population in NGC 1275. We can attempt to quantify the extent of star formation in this cluster if we assume that the blue continuum light is dominated by massive stars and use the measured flux to normalize an assumed IMF. Since the contrast between the galaxy and star cluster light is maximum at blue wavelengths, we expect our absolute flux measurements for the cluster to be most reliable in this region. Using our dereddened flux at an intrinsic wavelength of 4000 Å, we normalized a Salpeter (1955) IMF $[N(M)dM \propto M^{-(1+x)}dM,\ x = 1.35]$ assuming the measured light was dominated by O-type stars in the mass range 18–50 $M_\odot$. This normalization corresponds to ~9300 O-type stars within these mass limits. Integrating the resulting mass function between 0.1 and 50 $M_\odot$ yields a total cluster mass of $\sim 5 \times 10^6\ M_\odot$, or about the mass of the largest globular clusters associated with our Galaxy. We used the same normalization to estimate the production rate of ionizing photons in O-type stars. The luminosity of H$\alpha$ can then be predicted using the ratio of 2.2 ionizing photons per H$\alpha$ photon for case B recombination (Osterbrock 1989). The resulting predicted H$\alpha$ flux is $2 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$, which compares well (considering the assumptions required) with our observed, extinction-corrected H$\alpha$ flux of $5 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$.

The value of the cluster mass derived above is significant since it provides some estimate for the size scale of unstable growing modes in the keV gas. We can also use the mass to estimate the contribution of this star-forming region to the total accretion rate. If we assume that the time period in which the observed cluster would be detectable is comparable to the lifetime of a late O-type star, i.e. $\sim 8 \times 10^6$ yr, the $\dot{M}$ represented by this object is $\sim 0.6\ M_\odot$ yr$^{-1}$, and NGC 1275 should harbor $\gtrsim 200$ of these objects or their equivalent in newly formed stars. This estimate assumes, of course, that all of the accreted mass goes into the formation of stars, and that the star cluster reported here is typical of star formation regions in this cooling flow. Global measures of star formation for NGC 1275 are clearly inconsistent with this prediction (Romanishin 1987).

A steeper IMF for this star-forming region will increase the total mass implied by our measurements; for example, increasing $x$ to 2.0 implies a total cluster mass of $\sim 7 \times 10^7\ M_\odot$, or ~14 times the Salpeter result. This scenario would be approximately consistent with the observational requirement of star formation generating $\gtrsim 10$ times the mass of stars inferred for normal IMF production. A direct determination of the total mass in the star cluster would constrain possible IMFs. Optical continuum light is apparently dominated by the most massive stars and consequently provides little information on the low-mass component. A dynamical estimate may be possible from widths of the emission lines, however. Terlevich and Melnick (1981) and Melnick *et al.* (1987) reported a correlation between H$\beta$ luminosity and line width for giant H II regions that they argued is consistent with gas clouds moving at virial velocities in these clusters. A velocity width for emission lines in the NGC 1275 H II region that is excessive compared to the usual empirical relation might indicate that star formation is occurring with a steeper IMF than is typical for star formation in galaxy disks. Emission lines in our current data are unresolved at a level that is nonrestrictive in this regard (FWHM $\lesssim 160$ km s$^{-1}$); we are consequently initiating a program of new observations with higher spectral resolution in order to address this issue.

## IV. DISCUSSION

While the location of this young cluster makes it of special interest for detailed study, its more general relevance for star formation in cooling flows depends on whether it is genuinely associated with the cooling flow and, if so, whether it is typical of star formation in the flow. This region is clearly unusual in that its emission-line surface brightness is substantially higher than that of most of the filaments in NGC 1275 (Fig. 1*b*). Given the substantial mass estimated above for the star cluster, one could posit that this region is actually an extremely small irregular galaxy that is experiencing a burst of star formation as it interacts with NGC 1275. The association of the cluster in position and velocity with the low-ionization filament does not follow easily from this picture but is not fundamentally inconsistent with it. Hu *et al.* (1983) and Unger *et al.* (1990) have argued that the morphologies of ionized gas in the high-velocity ($cz \approx 8200$ km s$^{-1}$) and low-velocity systems are suggestive of an ongoing collision between these objects. This scenario offers a further alternative for the origin of the cluster, namely that it represents stars formed in low-velocity gas that was shocked during the encounter.

Identification of the cluster with star formation in the Perseus cooling flow would be placed on a sounder footing if it were demonstrated that this region represents the bright end of a luminosity distribution of similar zones in NGC 1275, and that these phenomena are not restricted to a region of interaction between the high-velocity and low-velocity systems. In fact, evidence does exist for other sites of massive star formation in this galaxy. The long-slit data at PA = 62° contain spectra of nebulosity and a possible continuum source at 13″ (4.4 kpc) northeast of the galaxy nucleus that resembles the brighter H II region emission discussed in detail above. Adams (1977) reported two extended blue structures located far from known high-velocity material that may be faint OB associations. We hope to clarify the nature of these regions, and massive star formation in NGC 1275 more generally, with spectroscopy and multiband imaging now in progress.

Optical spectra of the inner regions of NGC 1275 appear dominated by features characteristic of A-type stars (Rubin *et* *al.* 1977), leading O'Connell and McNamara (1989) to argue that this galaxy provides the best case for an IMF that is truncated above $\sim 3\ M_{\odot}$. This scenario could be reconciled with our observations if the IMF varies spatially within the galaxy. However, if the young star cluster reported here is at all representative of star formation in cooling flows, star formation in these objects is *not* occurring with a truncated IMF that excludes high-mass stars.

An alternative scenario can explain the existing populations in NGC 1275, namely that the young population in the central region of the galaxy originated in a starburst episode approximately $10^8$ yr ago. Such a burst may have resulted from the interaction of a smaller member of the Perseus cluster with the central galaxy. In contrast to truncated or otherwise distorted IMFs (Scalo 1986), dynamically induced starbursts are on a firm observational and theoretical footing (Hernquist 1989), and galaxy collisions inevitably occur with relatively high rates in dense cluster environments. In this picture the spectrum of the inner region of NGC 1275 is then dominated by the brightest stars in the coeval starburst population, and O-type stars are expected to be absent. Star formation is also occurring over a more extended region in the cooling flow, as suggested by the star cluster discussed in this *Letter*, but probably at a rate indicated by the presence of massive stars generated in a nearly normal IMF. The true mass accretion rate of the central galaxy is then far less than predicted from simple deprojections of the cluster X-ray surface brightness, probably due either to heating by energetic phenomena in the cluster (e.g., magnetic reconnection, thermal conduction, cluster galaxy motions, the central radio source, supernovae) or to a long time scale of evolution of the flow (Meiksin 1990).

We thank M. Davis, M. Dickinson, C. Lacey, J. Najita, J. Schachter, H. Spinrad, and R. Walterbos for helpful discussions. This work was supported by CalSpace grant CS-66-89 and NSF grant AST-8957063. Lick Observatory receives partial funding from NSF through Core Block grant AST-8614510 to the University of California.

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