The 8–13 µm Spectrum of Arp 299C

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To Appear in
The Astrophysical Journal Letters
Abstract

Arp 299C is a $5 \times 10^{10} \, L_\odot$ infrared source in the merging galaxy system Arp 299. It is the most luminous object known that is not obviously associated with a galaxy nucleus. Our data show that the 8–13 $\mu$m spectrum of Arp 299C has a strong [NeII] emission line and emission features like those of polycyclic aromatic hydrocarbon (PAH) molecules. These emission features are characteristic of HII regions associated with a burst of star formation. We did not detect any high-excitation ionic lines characteristic of an active galactic nucleus (AGN), nor a deep silicate absorption feature that might indicate a hidden compact nucleus. We deduce that Arp 299C is powered by an intense burst of star formation.

Subject headings: galaxies: individual (NGC 3690/IC 694: Arp 299: Mkn 171) — galaxies: interaction: — galaxies: active — dust: unidentified features

1. Introduction

The interacting galaxy system Arp 299, also known as Markarian 171 and NGC 3690/IC 694, is relatively nearby ($D = 42 \, \text{Mpc}, \, H_0 = 75 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$), allowing detailed spatial study. It has a large far-infrared luminosity ($L_{\text{FIR}} \approx 5 \times 10^{11} \, L_\odot$; Soifer et al. 1987) and a disturbed morphology. Of the components identified by Gehrz, Sramek, & Weedman (1983), component C has the warmest near-infrared colors, with significant nonstellar continuum emission as short as 2.3 $\mu$m (Ridgway & Wynn-Williams 1993). Components A and B are identified with the nuclei of IC 694 and NGC 3690, respectively, but component C lies in or is projected against the disk of NGC 3690 about 1.7 kpc from the nucleus. Using its 25 $\mu$m flux density as a guide, Wynn-Williams et al. (1991) estimate that component C emits 10% ($5 \times 10^{10} L_\odot$) of the total bolometric luminosity of Arp 299. This exceeds the total far-infrared luminosity of the Milky Way by a factor of 3. It is also 40 times more luminous than any of the giant HII regions in M 101. Component C is the most luminous known region in the universe that is not definitely associated with a galactic nucleus.

The physical conditions in Arp 299C are also extreme. Based on a combination of $K$-band imaging and the CO(1–0) interferometry maps of Sargent & Scoville (1991), Wynn-Williams et al. (1991) estimate that object C might contain $7 \times 10^8 \, M_\odot$ of gas within a 200 pc diameter region. The mean density of such a region, 6000 atoms cm$^{-3}$, would be more than than 1000 times greater than the mean interstellar density in the plane of the Milky Way. Subsequently, Solomon, Downes, & Radford (1992) made HCN(1–0) observations of Arp 299C which confirmed the presence of large quantities of molecular gas with densities of the order of $10^4$ cm$^{-3}$.

The 10 $\mu$m spectral region is very useful for determining the dominant luminosity source of infrared galaxies. Roche et al. (1991) have shown that galaxies with AGNs produce either flat featureless spectra or deep silicate absorption, while those with luminous HII regions produce spectra that are dominated by emission bands of PAH molecules (Puget & Léger 1989) or other organic compounds (Duley 1989; Sakata & Wada 1989). There is a problem, though, when trying to distinguish between silicate absorption and a PAH-dominated spectrum based on narrowband photometry alone, since a silicate absorption feature can be mimicked by the combination of
rising thermal dust emission between 10 and 13 µm and the long wavelength shoulder of the very strong 7.7 µm PAH feature. We have therefore obtained an 8–13 µm spectrum of Arp 299C with resolution \( \lambda / \Delta \lambda \approx 50 \) order to distinguish between a silicate dominated and a PAH dominated source.

Fig. 1. The 8–13 µm spectrum of Arp 299C. The triangles are from Wynn-Williams et al. (1991). The solid line represents a 150 K blackbody fitted at 13, 20, and 25 µm. The dashed line is a least-squares fit of the spectrum of the Orion Bar between 10.9 and 11.7 µm. Note that the 7.7 µm PAH emission dominates the emission shortward of 9 µm, while the underlying continuum becomes increasingly important toward longer wavelengths. The redshifted positions of atomic and molecular hydrogen emission lines discussed in §3.3 are also indicated.

2. Observations and Data Reduction

The data were obtained in clear weather on the night of 1992 February 16/17 at the United Kingdom Infrared Telescope (UKIRT).\(^1\) We used the 32 element 10 and 20 µm cooled grating spectrometer (CGS3) with a 5.5″ full width at ten percent power circular aperture. Our aperture was centered on the 10.1 µm peak position given in Wynn-Williams et al. (1991), and the pointing was maintained to within 2″ by offset guiding on a nearby SAO star. Two grating positions were required to sample fully the spectrum yielding 64 data points spaced by 0.1 µm. The observations consist of 120 beam-switched pairs of 30 s each. Since two grating positions are required to

\(^1\) The United Kingdom Infrared Telescope is operated by the Royal Observatory, Edinburgh, for the U. K. Science and Engineering Research Council.
produce a fully sampled spectrum, the observations represent 2 hr of on-source integration, but only 1 hr per data point. Background subtraction was performed with a beam separation of 30″ in either the E–W or NE–SW directions; no significant differences in the data were found in the two chopping directions. We have rejected data that fell outside of the range 7.7–13.3 μm (observed frame) and near the 10 μm ozone feature, because of poor atmospheric transmission. We have also rejected two individual subspectra that deviated by more than 5 σ in their mean signal from the rest of the data. Thus the 1 σ error bars in the spectrum represent the error in the mean of 119 individual observations. For calibration purposes, we divided the spectrum by the spectrum of BS 4518 and multiplied it by a theoretical blackbody curve with $T = 4400$ K normalized at 10 μm to an assumed value of $N = 0.77$ mag. Since the difference in airmass between the calibration star and the source was <0.1, no airmass corrections have been applied. We estimate the absolute flux calibration to be better than 20%. When allowance is made for the very different spectral resolution used, our measured flux densities are in satisfactory agreement with the broadband photometry of Wynn-Williams et al. (1991) and Gehrz et al. (1983). Our wavelength calibration is based upon the spectrum of a krypton calibration lamp. We have not corrected the spectrum for terrestrial or solar motion.

Our spectrum of Arp 299C (Fig. 1) reveals a number of emission features superimposed on a strong continuum. The most obvious features are the 11.3 μm PAH band and the 12.81 μm [NeII] fine structure line. The weaker 8.6 μm PAH band is marginally detected. We will argue in §3.1 that the increase in flux density from 9.0 to 7.7 μm is a manifestation of the 7.7 μm PAH feature. In Table 1 we present the wavelengths and continuum-subtracted fluxes of the emission features we detect and of some features we might have seen but did not. The quoted errors are 1 σ for detections and 3 σ for upper limits. Following Aitken & Roche (1984), we have defined our continuum relative to the PAH bands to be at 8.2 and 9.1 μm for the 8.6 μm feature, and at 10.9 and 11.6 μm for the 11.3 μm feature in the rest frame to allow comparison with their work. The reality of, and possible identification of, an unidentified 12.41 μm feature is discussed in § 3.3.
3. Discussion

3.1. The PAH Bands and Possible Silicate Absorption

The clear presence of the 12.81 \( \mu m \) [NeII] and 11.3 \( \mu m \) PAH feature indicates that Arp 299C contains powerful HII regions. Our equivalent width for the 11.3 \( \mu m \) feature is comparable to other galaxies where the feature has been detected, although it is smaller than most (Roche et al. 1991). The clear detection of the 11.3 \( \mu m \) feature allows us to estimate how much of the remainder of the 8–13 \( \mu m \) emission from Arp 299C can be explained by emission from other known PAH features in the bandpass. As has been shown by Zavagno, Cox, & Baluteau (1992) using IRAS Low Resolution Spectrograph data, there is an excellent correlation between the strength of the 11.3 \( \mu m \) feature and the 7.7 + 8.6 \( \mu m \) feature over 3 decades in feature luminosity in galactic HII regions. Thus the spectral contribution of the very broad 7.7 \( \mu m \) PAH feature to the flux density in the 7.7–9.0 \( \mu m \) range can be predicted from the strength of the much narrower and more easily measured 11.3 \( \mu m \) feature.

We have used this relationship in Figure 1. The Orion Bar, which lies about 2' southeast of the Trapezium, is an ionization front that shows a particularly rich PAH spectrum. The most complete spectrum of the bar region is that published by Roche (1989). It incorporates the Kuiper Airborne Observatory 6–9 \( \mu m \) data of Bregman et al. (1989) and the high spectral resolution 10.7–13.2 \( \mu m \) observations of Roche, Aitken, & Smith (1989). This spectrum has been fitted to the data between 10.9 and 11.7 \( \mu m \) after first subtracting an underlying continuum that is assumed to have the form of a 150 K blackbody. The fit was performed by first shifting the Orion spectrum by 3130 km s\(^{-1}\) (Sargent & Scoville 1991) and then degrading the spectral resolution of the Orion spectrum to that of Arp 299C by means of a box average performed at our observed wavelengths. The box width was 0.179 \( \mu m \).

The excellent agreement between the observed and predicted spectrum in the 7.7–9.0 \( \mu m \) range means that it is not necessary to invoke any silicate absorption to explain the shape of the 8–13 \( \mu m \) spectrum of Arp 299. As is the case for many luminous galaxies detected by IRAS, the spectrum is entirely explicable in terms of emission by PAH grains and warm dust. If, following Zavagno et al. (1992), the flux of the PAH bands is given by about 15 times the flux in the 11.3 \( \mu m \) feature, then we can estimate the PAH luminosity of Arp 299C. This works out to about \( 2 \times 10^9 L_\odot \), or about 4% of the estimated bolometric luminosity of component C (Wynn-Williams et al. 1991).

3.2. Ionic lines

In Table 1 we list three ionic forbidden lines that are diagnostic of the level of excitation of the ionized medium in Arp 299C. The [NeII] line is the only one detected, which argues for a low degree of ionization. A further check is that the ratio of [NeII] to 11.3 \( \mu m \) PAH emission is about 0.9, which is quite typical of HII region galaxies (Roche et al. 1991). Using the Br\( \gamma \) flux measured by Doyon, Puxley, & Joseph (1992) in a similar aperture, we find a [NeII] to Br\( \gamma \) ratio of 56.
Table 1: Narrow Emission Features in Arp 299C

| Feature | Rest Wavelength (µm) | Flux (10^{-15} W m^{-2}) | Equivalent Width (µm) |
|---------|----------------------|---------------------------|----------------------|
| 8.6 µm  | 8.54^{+0.09}_{-0.06} | 1.2 ± 0.4                 | 0.11 ± 0.04          |
| [Ar III]| 9.0                  | < 0.6                     |                      |
| [S IV]  | 10.5                 | < 0.7                     |                      |
| 11.3 µm | 11.28^{+0.03}_{-0.05} | 1.8 ± 0.2                 | 0.22 ± 0.02          |
| ?       | 12.41^{+0.04}_{-0.07} | 0.6 ± 0.2                 | 0.06 ± 0.02          |
| [Ne II] | 12.81^{+0.01}_{-0.01} | 2.1 ± 0.2                 | 0.25 ± 0.03          |

This ratio is within a factor of 2 of our predicted value of 87 based on the assumption of Case B recombination theory, an electron temperature of 10,000 K, a cosmic NeII number abundance of $1 \times 10^{-4}$ relative to H^+ (Lacy 1982), and no collisional de-excitation ($n \leq 10^5$ cm$^{-3}$). Given the uncertainties involved in comparing data obtained with different instruments when there is some extended emission in the beam, this is fair agreement. And, given the nondetection of the higher ionization lines of other elements that would betray the presence of a harder radiation field than expected in a starburst, we can conclude, as in the previous section, that there is no evidence for an AGN.

In Figure 1 the rise in the Orion Bar spectrum near the 12.81 µm [Ne II] line is due to the 12.7 µm PAH feature (Roche et al. 1989). Because of the presence of a feature at 12.41 µm discussed in § 3.3 and our low spectral resolution, we are not able to estimate the contribution of the 12.7 µm PAH feature to our [Ne II] measurement with confidence. The fit in Figure 1 suggests that the correct choice for the [Ne II] continuum may be higher than our choice, so until this object is studied at higher spectral resolution, the [Ne II] line flux in the table could be considered an overestimate.

3.3. The Unidentified Feature at 12.41 µm

The apparent unresolved feature at a rest wavelength of 12.41 µm is a surprise. We should caution first that it is only 3σ above an uncertain continuum and thus may well be spurious. The atmosphere has a slight increase in opacity at this wavelength as well. We will consider two possible identifications, hydrogen recombination and molecular hydrogen emission. The feature is coincident within the uncertainties in wavelength with the H (7–6) hydrogen recombination line at 12.37 µm. The difficulty with this identification is that the measured strength of the 12.41 µm feature is 50 times stronger than we would predict based on the strength of the Brγ emission measured by Doyon et al. (1992). Such an identification would predict 4 magnitudes of
extinction at 2.16 \mu m assuming no absorption at 12 \mu m and Case B recombination theory. This in turn implies 40 magnitudes of extinction at V. This amount of extinction seems excessive, since the Lyman continuum luminosity implied by this is almost 5 times larger than the bolometric luminosity given by Wynn-Williams et al. (1991).

Molecular hydrogen has a pure rotational $J = 4 \rightarrow 2$ transition at 12.27 \mu m, and our measured line strength would be suggestive of model 27 of Black & Van Dishoeck (1987) when compared with observations of Doyon (1990). However, the implied recession velocity of the H$_2$ would be $6600^{+1000}_{-1700}$ km s$^{-1}$, which is significantly different from the velocity of the CO(1–0) of 3130 km s$^{-1}$. This identification therefore seems unlikely, especially since the CO(1–0) FWHM for Arp 299C is only 50 km s$^{-1}$ (Sargent & Scoville 1991).

A higher spectral resolution study would help to disentangle the possible 12.7 \mu m PAH feature from the [NeII] feature and at the same time clarify the existence of the 12.41 feature.

4. Conclusions

The 8–13 \mu m spectrum of Arp 299C is consistent with a luminosity source that does not produce extremely high-energy photons. We base this conclusion on the lack of high-excitation forbidden lines and the consistency of our [NeII] and the Br\gamma flux of Doyon et al. (1992). Further, since we can fit the spectrum with such a simple model based on PAH molecules and thermal dust emission without invoking silicate absorption to account for the shape of the spectrum, a luminous AGN in Arp 299C is not required by the data. The similarity between our spectrum and those of other starbursting galaxies implies that the main source of luminosity is probably star formation. Our fit to the spectrum, while quite simplistic, explains about 90\% of the emission. The apparent feature at 12.41 \mu m may not be real, and if it is real, probably cannot be identified with either hydrogen recombination or molecular hydrogen emission.

We would like to thank Drs. Tom Geballe, Martha Hanner, Dave Sanders, Kris Sellgren, and Alan Tokunaga for helpful discussions, and Joel Aycock for assistance at the telescope. This work has been supported under the NSF Grant AST-8919563. This work has benefited from the use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration.
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February 2, 1993, Honolulu