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GROUND-BASED 1- TO 32- $\mu$ m OBSERVATIONS OF ARP 220:  
EVIDENCE FOR A DUST-EMBEDDED "AGN"?

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ABSTRACT. New observations of the 10- and 20- $\mu$ m size of the emission region in Arp 220 are presented. We also give ground-based photometry from 1-32  $\mu$ m including measurements of the strength of the silicate feature at 10  $\mu$ m. The results show that the 20- $\mu$ m size of Arp 220 is smaller than 1.5 arcsec (500 pc); comparison of IRAS and ground-based observations show that IRAS 12- $\mu$ m flux measured with a large arcmin beam is the same as that seen from the ground with a 3-arcsec aperture. At 10  $\mu$ m a deep silicate absorption feature is seen that corresponds to a visual extinction of about 50 mag.

These results suggest that a very significant portion of the  $10^{12} L_{\odot}$  infrared luminosity from Arp 220 comes from a region less than or of the order of 500 pc in diameter. When these results are combined with recent measurement of a broad Brackett- $\alpha$  line by DePoy and an unresolved 2.2- $\mu$ m source by Neugebauer, Matthews and Scoville, a very attractive possibility for the primary luminosity source Arp 220 is a dust-embedded compact Seyfert-type nucleus.

INTRODUCTION

Arp 220 (IC 4553) is a relatively nearby galaxy that IRAS found to be extremely luminous at infrared wavelengths (Soifer et al. 1984). It has a total luminosity of  $10^{12} L_{\odot}$  at a distance of 70 Mpc ( $H_0 = 75$  km/sec/Mpc). It emits 50 to 100 times more luminosity at infrared than visible wavelengths. Optically the galaxy appears highly disturbed and has been classified as a merger (Joseph and Wright 1985). It contains several compact radio sources (Norris 1985) and at visual wavelengths shows a thick dust lane across its center (Schild 1985).

Arp 220 appears to be one of a number of galaxies discovered by IRAS that have a total luminosity  $> 10^{12} L_{\odot}$ . The space density of these galaxies is as high or higher than optical, radio, or x-ray selected galaxies or QSOs (Soifer et al. 1986). A critical question to be answered is the dominant source of energy in Arp 220. A number of suggestions have been made such as (1) a burst of star formation (Rieke et al. 1985; Joseph and Wright 1985), (2) a dust-embedded active galactic nucleus "AGN" (Soifer et al. 1984; Norris 1985), and (3) mechanical energy from a collision of two galaxies (Harwit et al. 1986). In this paper we present new observations that suggest that a dust-embedded "AGN" is the most likely explanation for the luminosity in Arp 220.

OBSERVATIONAL RESULTS

We present previously unpublished results on the size of the emission region at 10  $\mu$ m (N) and 20  $\mu$ m (Q). The data were obtained on the IRTF in March 1985 and 1986 using the facility photometer with a Ga:Ge bolometer and standard interference filters.

Figure 1 shows a 20- $\mu\text{m}$  profile of Arp 220 along a north-south line made with a 3-arcsec aperture. The data have been folded about the central point. Also shown is the profile of a star. Similar data also exist in the east-west direction. These data show that the galaxy and stellar profiles are similar; in other words Arp 220 is unresolved. Assuming that the two profiles are Gaussian in shape, the Arp 220 source has a characteristic size (FWHM) which is less than 1.5 arcsec. This corresponds to  $<500$  pc at the distance of Arp 220.

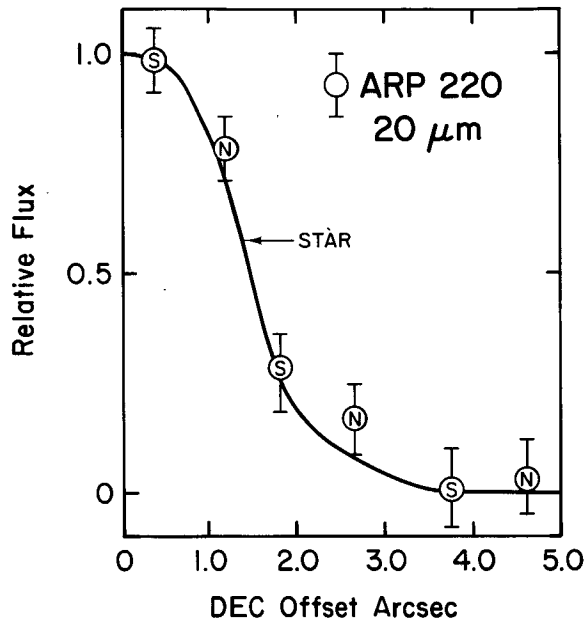


Figure 1: North-south profile at 20  $\mu\text{m}$  taken with a 3-arcsec beam.

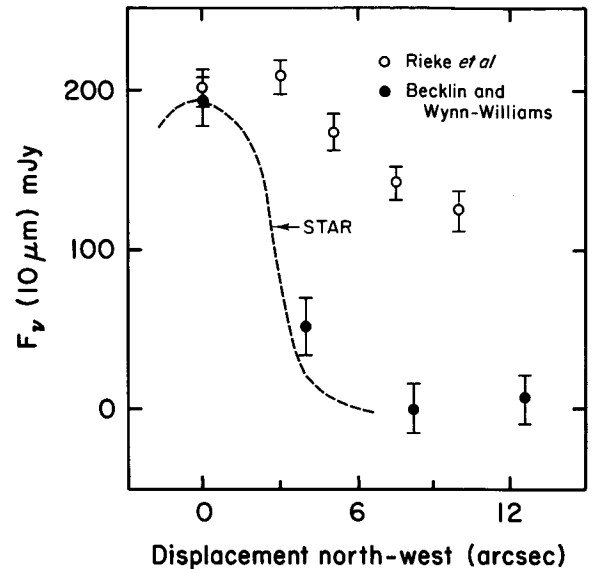


Figure 2: North-west profile at 10  $\mu\text{m}$  taken with a 5.5 arcsec beam.

A 10- $\mu\text{m}$  profile with 5.5-arcsec resolution along a north-west direction is shown in Figure 2 along with the profile of a star; again Arp 220 is unresolved. These data disagree with the results of Rieke et al. (1985) whose data are also shown in Figure 2. Both observations were made with the same system on the IRTF; we do not understand the discrepancy. The 20- $\mu\text{m}$  profile and the 12.5- $\mu\text{m}$  aperture growth curves discussed below would suggest that the present results, which show that the source is unresolved at 10  $\mu\text{m}$ , are correct.

Figure 3 is an aperture growth curve at 12.5  $\mu\text{m}$ , i.e., flux versus aperture size. It includes ground-based observations with beam diameters of 3.0, 5.5, and 7.0 arcsec and the IRAS data with a beam  $>1$  arcmin in diameter. The IRAS point has been corrected for the different filter responses using the energy distribution for Arp 220 given below. The result is that  $>90\%$  of the 12.5- $\mu\text{m}$  flux measured by IRAS is observed in a 3-arcsec-diameter aperture.

In Figure 4 we present the energy distribution of Arp 220 from 7.8- to 12.5- $\mu\text{m}$  observed with a 5.5-arcsec aperture and standard IRTF filters with  $\Delta\lambda/\lambda \sim 0.1$ . There is an obvious deep absorption feature at 10  $\mu\text{m}$ . The shape of the feature agrees with that seen in other galactic and extragalactic sources and is ascribed to silicate dust (Roche et al. 1986). The shape of the spectrum indicates an absorption optical depth of  $\tau \sim 3$ , implying a visual dust extinction of  $A_V \sim 50$  mag.

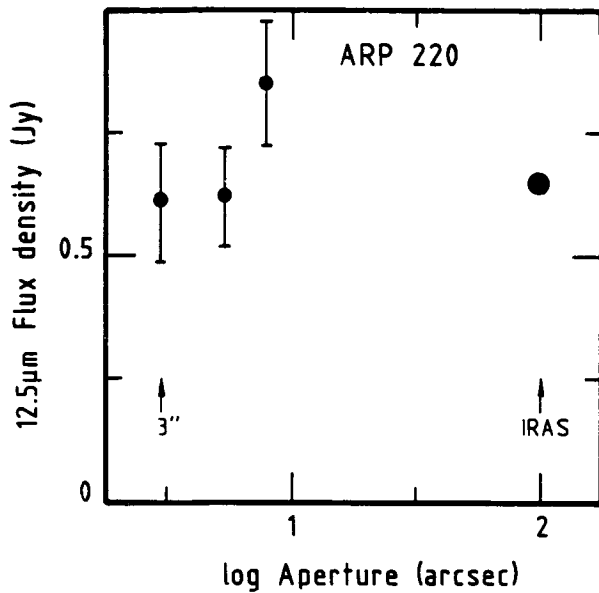


Figure 3:  
Aperture growth curve at 12.5  $\mu\text{m}$ .

Figure 4:  
Energy distribution  
from 7.8 to 12.5  $\mu\text{m}$ .

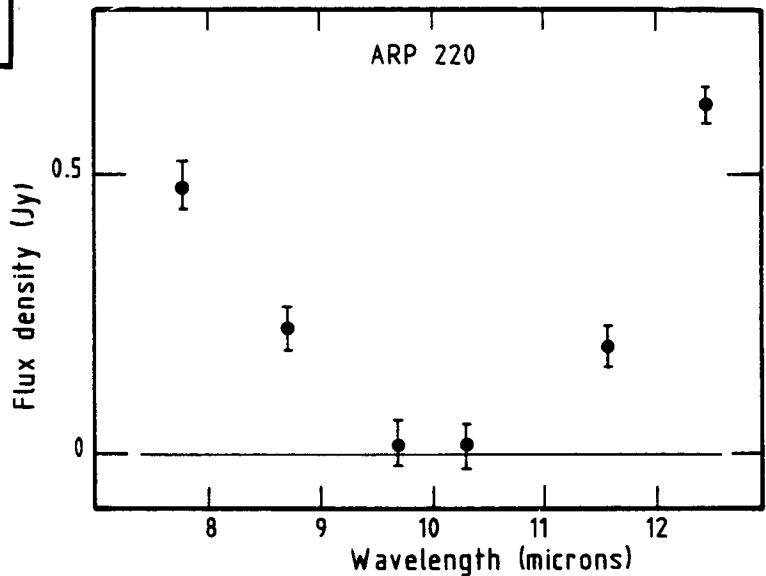


Figure 5 shows the complete spectrum of Arp 220 from 1  $\mu\text{m}$  to 350  $\mu\text{m}$  plotted as  $\log vS_v$  vs  $\log v$ ; both IRAS and ground-based data are shown. The 1.65-, 2.2-, and 3.8- $\mu\text{m}$  points are unpublished University of Hawaii measurements in a 4-arcsec aperture that have had an estimated stellar contribution subtracted. All of the points from 7.8 to 32  $\mu\text{m}$  were made with a 5.5-arcsec aperture on the IRTF. The 350- $\mu\text{m}$  point is from Emerson et al. (1984). The energy distribution shows that:

- 1) The energy peaks at about 50  $\mu\text{m}$ ; the distribution corresponds to a blackbody at a temperature of 62 K (Soifer et al. 1984).
- 2) Silicate absorption is a dominant feature.
- 3) The IRAS fluxes at 25 and 60  $\mu\text{m}$  are consistent with the observed ground-based fluxes at 20 and 32  $\mu\text{m}$  measured with a 5.5-arcsec aperture.

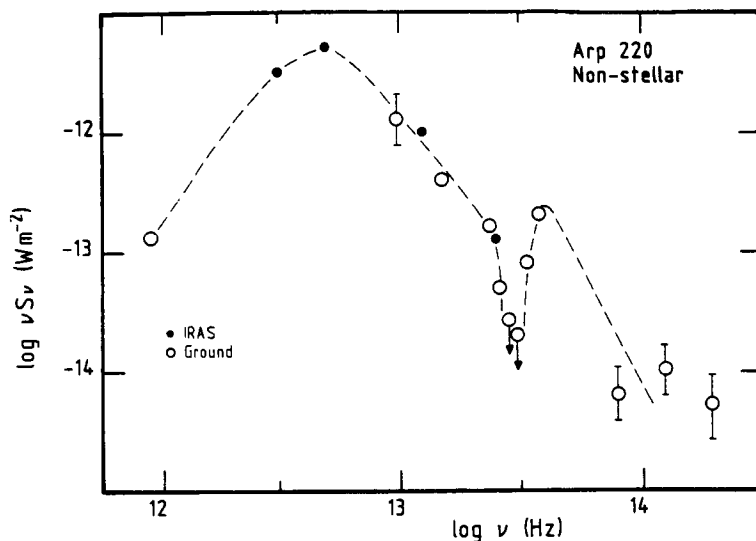


Figure 5: Energy distribution from 1 to 350  $\mu\text{m}$ .

A 6-cm VLA map with 0.4-arcsec resolution is shown in Figure 6. It shows two slightly resolved sources ( $\theta \sim 0.2$  arcsec) separated by about 1 arcsec in right ascension. The structure we see at 6 cm differs significantly from the triplet morphology found by Norris (1985) using the MERLIN array at 18 cm. We have not yet established whether this difference is attributable to time variability, spectral index variations, or to differences in the data reduction procedure. The compact 10- and 20- $\mu\text{m}$  source lies within 1 arcsec of the midpoint of the radio peaks; this has been determined by offsetting the IRTF from nearby AGK<sub>3</sub> stars.

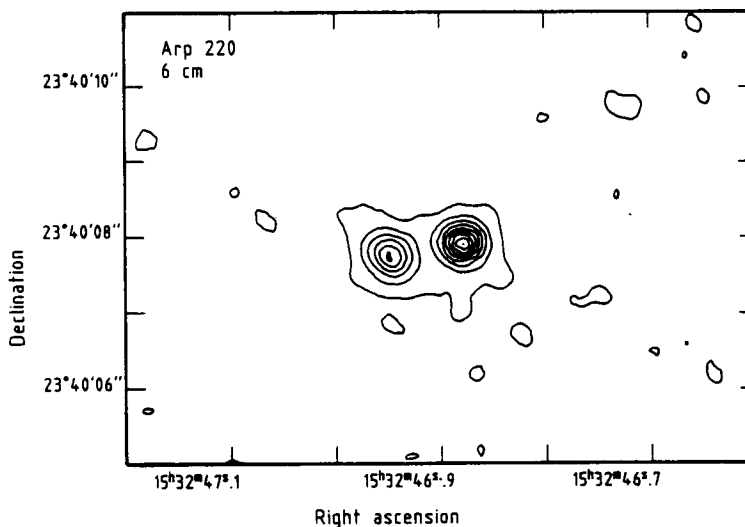


Figure 6: VLA 6-cm map.

#### NEW OBSERVATIONS BY OTHERS

A student of ours at the Institute for Astronomy (D. DePoy) has measured the Brackett- $\alpha$  line at 4.1  $\mu\text{m}$  on the UKIRT using CGS2 with a 5.5-arcsec beam. From his results, presented at this conference (DePoy 1986), he finds that the line is broad ( $\sim 1300$  km/sec FWHM). The line strength implies an infrared excess  $[L_{\text{bol}}/L_{\text{Ly}\alpha} - 1] \sim 300$ . Correction for the reddening based on the sili-

cate absorption depth would reduce the excess to about 100. Because the 32- $\mu$ m flux originates from a region (Figure 5) with the same angular diameter as the beam used for the  $B_\alpha$  measurements, no correction for aperture size is necessary.

The Palomar infrared group has made slit scans of Arp 220 at 2.2  $\mu$ m using the 200-inch telescope (Neugebauer, Matthews, and Scoville 1986). These data are shown in Figure 7 along with a scan of a star; the slit width was  $\sim 1.0$  arc-sec. Model fits with Gaussian profiles indicate that there is an unresolved source at the center with a limit to the full width at half maximum of 0.2 arc-sec and a 2.2- $\mu$ m flux of 8 mJy. Correcting for the reddening discussed above implies an intrinsic 2.2  $\mu$ m-flux of 500-1000 mJy.

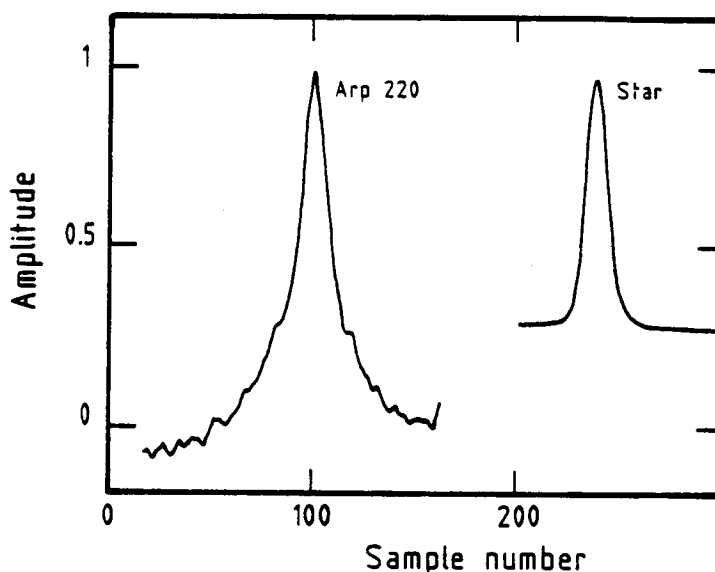


Figure 7: Slit scan at 2.2  $\mu$ m from the 200-inch (Neugebauer, Matthews and Scoville 1986).

## DISCUSSION

### A. Thermal Infrared Component

The energy distribution shown in Figure 5 suggests that the emission mechanism in Arp 220 is thermal emission from dust (Soifer et al. 1984). If half of the 20- $\mu$ m flux observed in the 3-arcsec beam is coming from a region whose diameter is equal to or less than 1.5 arcsec, then the brightness temperature at 20  $\mu$ m is greater than or equal to 60 K. From the spectrum the color temperature is about 62 K (Soifer et al. 1984). Thus the optical depth in emission at 20  $\mu$ m is close to one. This agrees well with the depth of the silicate absorption feature at 10  $\mu$ m if  $\tau_{9.7} \sim 2 \tau_{18}$ ; such a relationship is observed in galactic sources (Forrest et al. 1979).

Because the source is thick at 20  $\mu$ m and emits approximately like a blackbody at its 20- $\mu$ m brightness temperature, it is very probable that much of the longer wavelength emission near the peak of the energy distribution is coming from a region  $\theta \sim 1.5$  arcsec ( $\sim 500$  pc in diameter). Although radiative transfer effects could make the emission region at 50  $\mu$ m somewhat larger than at 20  $\mu$ m, it should be noted that this size is consistent with a 50- $\mu$ m upper limit to the size of 8 arcsec measured by Joy et al. (1986) from the KAO and our 32- $\mu$ m measurement with a 5.5-arcsec beam (Figure 4). The infrared radiation from

Arp 220 appears highly concentrated toward the center.

#### B. 1- to 3- $\mu$ m Infrared Component

Both the 2.2- $\mu$ m scan on the 200-inch telescope and our unpublished aperture studies from the IRTF, show that there is a component in the 1.65- to 3.8- $\mu$ m range which may not be stellar; it is observed to be about 10 mJy at 2.2  $\mu$ m or 500 mJy when corrected for reddening. If this component has a spectrum similar to the QSO 3C273, then its total luminosity would be of the order of  $10^{12} L_{\odot}$ .

#### C. Collisional Energy

The present observations can be used to test the various luminosity sources in Arp 220 that have been suggested to date.

The model of Harwit et al. (1986) which predicts the amount of mechanical energy converted into infrared luminosity when two galaxies merge does not give a size for the emission region. Such a mechanism would not appear to naturally explain the emission size that we observe.

#### D. Star Formation

The hypotheses that a burst of star formation is the primary energy source in Arp 220 has a number of problems in light of the present set of observations.

One of the strongest arguments used to support star formation has been extended 10- $\mu$ m emission (Rieke et al. 1985; Joseph and Wright 1985). The observation of extended 10- $\mu$ m emission in Arp 220 appears to be in error. The surface density of star formation that is required in Arp 220 is 25 times larger than in M82; prior to IRAS, M82 had one of the highest densities of nuclear star formation. Is it reasonable to have such a rate of star formation in such a limited volume? Also a region of star formation in the central 500 pc of Arp 220 should have a corresponding 500-pc diameter radio source, but only two sources <50 pc diameter are seen at 6 cm.

Several parameters that are used to determine the amount of star formation have also been measured in Arp 220. These include the Brackett- $\alpha$  line strength which gives the number of ionizing photons (DePoy 1986), the CO line strength which gives an estimate of the interstellar material (Sanders and Mirabel 1985), and the 2.2- $\mu$ m continuum which gives a limit on the number of M supergiants. In each case, if one scales from M82 using the total luminosity, one finds that the star formation indicators are a factor of 10 less than expected. There appears to be very little evidence for star formation producing more than 10% of the observed luminosity in Arp 220.

#### E. An Active Nucleus

There does appear to be a number of observations that suggest that a compact active nucleus is the primary luminosity source in Arp 220. It is the easiest and most natural way to explain the compact infrared morphology. This includes both the direct size measurement and the deep silicate absorption feature. It is also the easiest way to explain the compact radio sources, the

broad Brackett- $\alpha$  line, and the presence a point-like 2- $\mu$ m source. The latter source, in fact, could contain enough energy to produce the observed infrared luminosity, if it is a power law source in the uv and x-ray region.

In summary, the present observations are consistent with the idea that more than 90% of the luminosity in Arp 220 originates from a radio quiet active nucleus.

#### SPECULATION

Based on Arp 220, MKN 231, NGC 6240, and NGC 1068 it appears that both a burst of star formation and an active nucleus are present in luminous IRAS galaxies. A burst of star formation produces  $L \sim \text{few} \times 10^{11} L_{\odot}$ . If  $L \sim 10^{12} L_{\odot}$ , the dominant source of luminosity is a radio quiet active nucleus. Since interstellar material certainly feeds the star formation, it is natural to speculate that it also feeds the active nucleus.

#### ACKNOWLEDGMENTS

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#### DISCUSSION

##### HARWIT:

The small size of Arp 220 is impressive. In the model we presented yesterday, we took 2 kpc diameter  $\times$  0.1 kpc thick disks colliding with each other in order to accommodate  $10^{10} M_{\odot}$  of  $H_2$  at a normal molecular density of  $n \sim 10^3 \text{cm}^{-3}$ . We know that Arp 220 has that much gas from CO observations. Its compactness simply says densities are higher; but that does not affect the way such a model works. Higher densities tend to lead to higher luminosities for a given size source.

BECKLIN:

That is the nice thing about a theoretical model, it can always be fixed up to agree with observations.

UNGER:

The radio continuum emission at 18cm has an extent of about 1.5 arcsec, rather larger than at 6cm. You give an upper limit to the angular extent at  $20\mu\text{m}$  of 1.5 arcsec - can you push this upper limit any further to say that the radio and  $20\mu\text{m}$  emission aren't coincident?

BECKLIN:

That is unlikely, since if the source is thermal, it cannot be made smaller than 1.5 arcsec.

ELIAS:

Since you know the approximate size of the 20 micron source, and also that it has an optical depth of at least 1, what is the minimum amount of dust required?

BECKLIN:

About  $10^7 M_{\odot}$  in dust. If the dust to gas ratio is 0.01 by mass, this corresponds to  $10^9 M_{\odot}$  in gas, not too different from the amount estimated from the CO.

YOUNG:

Could you please elaborate on the point that the CO is too low by a factor of 5. Given the  $M(\text{H}_2)$  and the dust temperature in Arp 220, the  $L_{\text{IR}}/M(\text{H}_2)$  ratio is precisely what you expect for a galaxy with Arp 220's  $S_{60}/S_{100}$  ratio.

BECKLIN:

For a 'typical' star forming region there is a 'standard'  $L_{\text{IR}}/M(\text{H}_2)$  ratio. If  $L_{\text{IR}}/M(\text{H}_2)$  is larger than this ratio, physics demands that the dust temperature increase (unless  $M_{\text{dust}}/M(\text{H}_2)$  were also larger). As pointed out by Phil Solomon, your relationship has physical significance, but not astrophysical significance. Astrophysically, Arp 220 has a larger  $L_{\text{IR}}/M(\text{H}_2)$  ratio than 'standard' star forming galaxies.

TELESCO:

As you know, in NGC 1068 the  $10\mu\text{m}$  emission comes from a very compact region, whereas the far-infrared luminosity originates from a much larger region. So you have to be careful in concluding that all the luminosity of Arp 220 comes from a region 500 pc in size.

BECKLIN:

I know very well that we have not proven a thing. However, unlike NGC 1068, Arp 220, from its spectrum, appears to have only one component, which is thick at  $20\mu\text{m}$ .