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TWO BLUE ARCS ASSOCIATED WITH THE cD GALAXY OF ABELL 963

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ABSTRACT

We have found two blue arcs associated with the cD galaxy in Abell 963. They are different in physical length, angle subtended, and distance from the nucleus of the cD, are on opposite sides of the cD galaxy, and both arcs appear concentric about the nucleus. The arcs are patchy and extremely blue, having colors bluer than the bluest members of the Abell 963 cluster. The cD galaxy is highly elliptical, $\epsilon \approx 0.5$, with one, possibly both arcs, being bisected by the major axis of the cD. We suggest the most likely mechanism for the origin of the arcs is gravitational lensing of a high-redshift galaxy by the cD galaxy and the associated cluster core.
Subject headings: galaxies: clustering — gravitational lenses

I. INTRODUCTION

The discovery of "blue arcs" in two clusters of galaxies, Abell 370 and Cl 2242−02 (Soucail *et al.* 1987*a*; Lynds and Petrosian 1986), has led to both excitement and speculation as to their origin. Such large coherent geometrical structures can be difficult to explain, especially in the dynamically active environment that exists in the cores of rich clusters of galaxies. These conditions may explain why the arcs appear to be quite rare. Lynds and Petrosian found only two arcs in a sample of 57 giant elliptical galaxies and no arcs were apparent in a sample of over 400 clusters observed by J. E. Gunn and D. P. Schneider (private communication to Braun and Dekel 1987).

A better understanding of the nature of these arcs may be accomplished in two manners. First, surveys to increase the number of known arcs should give insights into how common arcs are and constrain or expand the circumstances and environments in which the arcs exist. Second, spectroscopic observations should provide clues as to the origin of the light and why it is so blue. These observations are difficult due to the faintness of the arcs. Soucail *et al.* (1987*b*) have made a tentative redshift identification of 0.59 for the arc in A370, whose redshift is 0.373. But, the area of the arc observed by them deviates significantly from the circular pattern and may not actually be associated with the arc. Several other attempts to observe spectral features have reportedly failed.

In this *Letter*, we report the discovery of two blue arcs in the cluster Abell 963.

II. OBSERVATIONS

The observations were made at the Cassegrain focus of the University of Hawaii 88 inch (2.2 m) Telescope of the Mauna Kea Observatory on 1987 March 30. The detector was the UV-flooded, backside-illuminated Galileo/IfA 500 × 500 three-phase TI CCD (Hlivak, Henry, and Pilcher 1984). A focal reducer was used which produced an image scale of 0".33 per pixel.

Images of the cD galaxy in Abell 963 were obtained in the Johnson *B* band and the Kron-Cousins *R* band. The exposure times were 30 minutes in *B* and 15 minutes in *R*. The seeing was 1". Flat fields were taken off the inside of the dome using a lamp with a blue filter matched to roughly reproduce the night sky continuum. Standard stars were from the M92 standard star field (Heasley and Christian 1986).

III. DATA

The B image of the cD galaxy of Abell 963 and the associated arcs is presented in Figure 1 (Plate L1). We believe this is the first case in which two arcs have been found in one cluster. It is quite obvious that the light distribution along the arcs is patchy. The arcs are at opposite sides of the cD, and both lie in its extended envelope. The larger arc is to south of the cD galaxy, is 18".5 from the center of the cD, and subtends an angle of 70°. Assuming the arc is at the distance of the cluster, with a redshift of 0.206, it is 40 h^{-1} kpc from the center of the cD and has a linear size of 49 h^{-1} kpc ($h = H_0/100$ km s^{-1} Mpc^{-1}). The smaller northern arc is 12" from the center of the cD and subtends an angle of 30°, which gives a distance of 26 h^{-1} kpc from the nucleus and a physical length of 14 h^{-1} kpc. Both arcs are unresolved ($\leq 1''$ FWHM) and appear to be concentric about the center of the cD.

Because the arcs are in the envelope of the cD, it is difficult to measure their magnitudes and colors accurately. For the southern arc, first, a copy of the image was made and an average sky value was subtracted. This image was flipped about both axes and shifted so that the centers of the cD on it and the original image coincided. Then the skyless image was subtracted from the original image. This procedure reproduced the average sky value on each side of the larger arc to better than 2% of the original average sky value. This procedure was followed for both the *B* and *R* images. The flux in a box of 3".6 by 9".5 which enclosed the two brightest patches of the arc was measured in each band, giving $B = 22.3$, $R_{KC} = 21.6$, and a $B - R_{KC}$ of 0.7.

Due to the two objects $\sim 11''$ south of the cD nucleus, it was not possible to measure the magnitudes of the northern arc in a similar manner as was done for the southern arc. A rough measurement was made by measuring the flux in a box around the arc and then subtracting off the sky and galaxy flux determined by the average on both sides of the arc. This gave $B = 23.6$, $R_{KC} = 23.1$, and $B - R_{KC} = 0.5$, somewhat bluer

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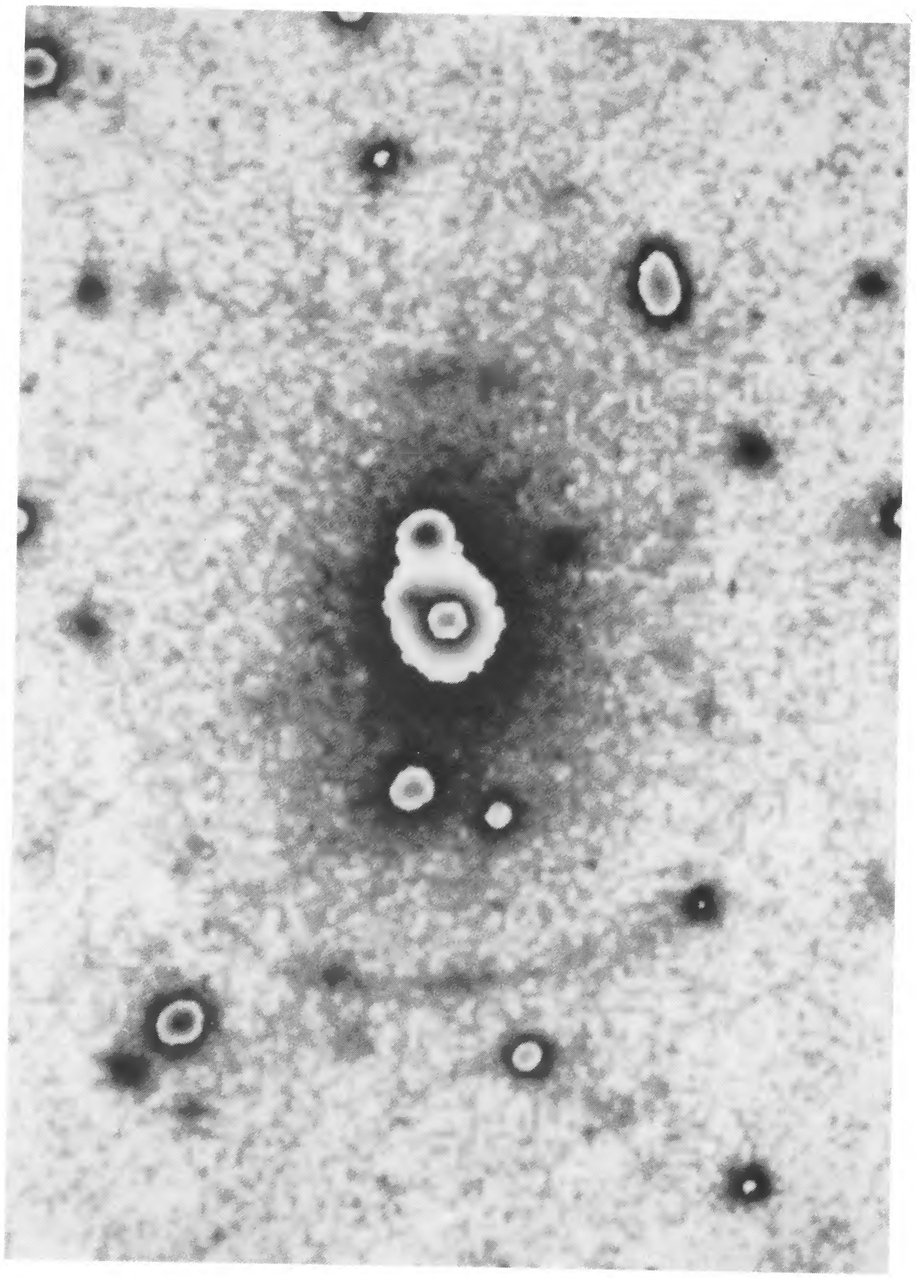

FIG. 1.—The *B* image of the cD galaxy of Abell 963 and the two associated blue arcs. The separation of the arcs is 30″. Note the diametrically opposed structure in the arcs. North is up, and east is to the left.

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than the southern arc. We believe the errors on this color are large, due to the faintness of the arc in the R band and the crude method of measurement, so that the colors of the arcs are probably the same.

The color of the arcs can be compared to the color of two blue galaxies in the cluster field. Butcher, Oemler, and Wells object 60 (1983, hereafter BOW) is a strong emission-line starburst galaxy (Lavery and Henry 1986) with [O II] $\lambda3727$ equivalent width ~ 100 Å, and BOW object 142 is a Seyfert 2 AGN (Lavery and Henry 1988). The $B - R_{KC}$ colors of these two galaxies are 0.82 and 0.98, respectively. Given the errors on the colors of 0.05, it is certain that the arcs are at least as blue as, probably bluer than, these strong emission line objects.

The larger arc may be associated with a galaxy located at the west end, BOW object 238. It has a rest frame $B - V \approx 0.75$, and we have determined a $B - R_{KC}$ of 1.7. Assuming the object is a cluster member, it is somewhat blue in color, but not nearly as blue as the arc. It may be possible that the galaxy is somewhat blue due mostly to contaminating light from the arc.

The cD galaxy is large, having a major axis diameter of 110 h^{-1} kpc at a R_{KC} surface brightness of 25th mag per square arcsecond and has an ellipticity of 0.5. It is interesting that the arcs are quite close to being along the major axis of the galaxy. Embedded within the cD is an object just 2″ to the northeast. The proximity of the object to the nucleus of the cD makes it interesting if one wishes to invoke nuclear activity as a possible explanation for the production of the arcs. The color of the object was measured in a similar manner as the southern arc, giving a $B - R_{KC} = 1.8$, somewhat bluer than E/S0 galaxies at this redshift.

IV. DISCUSSION

A number of mechanisms have been suggested to explain the origin of the arcs. These can be divided into two categories. First, some special event associated with the nucleus of the cD galaxy that produces star formation or synchrotron radiation. Second, involvement of a background object, such as a QSO, which produces the arcs through a "light echo" or by gravitational lensing. Braun and Dekel (1987) give an excellent discussion of these various mechanisms.

We favor the origin of the arcs as being due to gravitational lensing of a background galaxy, as originally suggested by Paczyński (1987), for the following reasons: (1) Their appearance is quite close to that expected from a classical gravitational lens model, (2) there appears to be corresponding structure in the arcs diametrically across the center of the cD galaxy, and (3) the extreme color of the arcs suggests that they are not members of the cluster. In the three known cases, the arcs appear to be concentric about the center of mass of a cluster. In A963 and Cl 2242−02, the center of mass appears to be dominated by a single galaxy. In A370, the lensing object may be the cluster itself.

Discussions of the changes of the images produced by a circularly symmetric gravitational lens as the background object is moved off-axis is presented in Refsdal (1964) and Leibes (1964). If the background object is directly behind the lensing object, the image produced by the gravitational lens is a ring (Einstein 1936). As the object is moved off-axis, the image becomes a circle with one side thicker than the other. As the off-axis distance is increased, the image becomes two arcs on separate sides of the galaxy. Leibes's Figure 2 provides a series of sketches that illustrates the changes as the object is moved off-axis. The arcs of A963 are probably an example that lies between (a) and (b) of this figure.

Turner, Ostriker, and Gott (1984) have modeled the lensing of a background object by a cluster of galaxies. They do not model lensing by a cluster without a dominant central galaxy, believing the possibility of observing such lensing is very small. But this may be what is occurring in A370. The models they produced consisted of a single cD galaxy and a uniform density sheet, representing the cluster, superposed on the cD. They find that the cluster will affect the lensing of the cD only if it is extremely rich and concentrated, such as the Coma cluster, whose core has a very high galaxy surface density. Though the properties of Cl 2242−02 have not been well determined, A370 and A963 are two such rich, concentrated clusters. Butcher and Oemler (1984) have defined a concentration index, C, as

$$C \equiv \log \frac{R_{60}}{R_{20}} ,$$

where R_{20} and R_{60} are the radii that contain 20% and 60% of the cluster galaxies. They find both A370 and A963 to be slightly more concentrated than the Coma cluster, with values of C equal to 0.59 and 0.60 compared to 0.53 for the Coma cluster. Both clusters are also quite rich when compared to the Coma cluster. Coma is Abell richness class 2, A963 is richness 3, and A370 was classified as richness 0, but this is probably very much underestimated (Butcher, Oemler, and Wells 1983). Butcher and Oemler (1984) have also measured the richness of Coma, A370 and A963, finding them to be essentially equal. From their models, Turner, Ostriker, and Gott (1984) find the cluster enhances the lensing of the cD galaxy, producing image separations in the range of 30″–60″. The separation in the case of A963 is 30″.

What needs to be explained if gravitational lensing is producing the blue arcs is how apparent single arcs of obvious curvature can be produced. It is possible that in some cases, the brightness ratio between the two images can become quite large, making the second image too faint to be observed; or the second image may be obscured or dispersed by another galaxy in the cluster. Finally, it is possible that the assumption of a circularly symmetric lens is too simplified. Asymmetric lenses may be able to produce single, large, circular arcs (Grossman and Narayan 1988).

To determine the nature of the background object, it would be necessary to obtain a spectrum of it. But it is possible to use the color of the arc to place some constraints. Using the color transformations of Fernie (1983), the arc has a $B - R$ in the Johnson system of ~ 0.85. Coleman, Wu, and Weedman (1980) presented the $B - V$ and $V - R$ colors as a function of redshift for various galaxy types. Only at redshifts of 1 or greater is it possible that any normal galaxy has the correct color and even then it is only galaxies of the Magellanic Irregular type. This suggests the lensed object is a quasi-stellar object or a galaxy that contains an active nucleus.

But the fact that the arcs are patchy in appearance may indicate that the background object is an extended source, i.e., a galaxy. Lensing models for an extended background object use a uniform surface brightness. Such a background source should produce arcs of the same surface brightness (Leibes 1964). The patchiness of the arcs may indicate that the lensed object also has a patchy light distribution. It is also interesting that the lines that connect the two brightest patches in each arc

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cross extremely close to the nucleus of the cD. It may be that these bright areas are two images of the same region of the background object.

We have constructed a simple lens model that reproduces the main characteristics of the arcs. We attempted to model everything but the faint westward extension of the southern arc because our images are not deep enough to detect the corresponding structure in the northern arc, if it exists. The model consists of a point mass (the cD galaxy) embedded in a uniform mass sheet (the cluster). The input parameters are the mass of the point and the ratio of the surface density of the sheet to the critical surface density, $\Sigma_{cl}/\Sigma_{crit}$, where the critical surface density is that necessary for the sheet to produce images by itself. The formalism is from Leibes (1964) and Turner, Ostriker, and Gott (1984).

The value of $\Sigma_{cl}/\Sigma_{crit}$ depends on the velocity dispersion, the core radius, and redshift of the cluster and the redshift of the source. Since this quantity depends weakly on the source redshift, except if the source is very close to the cluster, we used a redshift of 1. We determined a velocity dispersion from the redshifts of seven red galaxies (Lavery 1988) of 1100 $\pm$ 480/210 and used a core radius of 27″ $\pm$ 12″ (Thompson 1986). These values give $\Sigma_{cl}/\Sigma_{crit} = 1.37 \pm 1.35/0.80$, a rather poor determination. We have determined $\Sigma_{cl}/\Sigma_{crit}$ for the Coma cluster at the redshift of A963, using the values of the parameters given in Kent and Gunn (1982), giving $\Sigma_{cl}/\Sigma_{crit} = 0.4 \pm 0.08$. We have adopted a value of 0.7, which is consistent with the data and was chosen to allow the background galaxy to be similar to the LMC in absolute *B* magnitude.

A number of parameters come out of the model. The undeflected location of the source, which is proportional to the difference of the distances of the two arcs from the center of the cD, is 2″ south of the cD nucleus. The mass of the point, which is proportional to the product of the distances of the two arcs from the cD nucleus, is $5.8 \times 10^{12}\ h^{-1}$ solar masses. The diameter of the source, determined by the lengths of the arcs, is 0″.8. The two bright spots in both arcs are matched in this model if the source has two bright patches separated by 0″.8. This implies a physical size of 4.75 h^{-1} kpc, which is consistent with the size of the LMC of 9.3 kpc.

There are three observable quantities that can be used to test the model. First, the model predicts a brightness ratio of 2.4 for the arcs and we measure a ratio of 3.3. Second, the widest part of the arcs should be 1″, and we observe the arcs to be unresolved ($\leq$1″ FWHM). Considering the simplicity of the model and the difficulty in measuring the properties of the northern arc, we feel these numbers are in good agreement.

The third check on the plausibility of the model comes from the surface brightness of the arcs. The area of the large arc is approximately 10″ by 1″, which gives a blue surface brightness, μ_B, of 24.8 mag per square arcsecond. Two corrections must be made to μ_B, the *K*-correction and the cosmological surface brightness term, $(1 + z)^{-4}$. From Pence (1976), galaxies of type Sdm–Im have $K \approx 0.45$ mag and for a redshift of 1, the cosmological term is an additional 3 mag. This gives a net surface brightness of 21.35. This compares quite well with the central surface brightness of the LMC, $\mu_B = 21.5$ (Freeman 1970), considering this is for the brightest patches of the arc, and with the average central μ_B of 28 galaxies (Freeman 1970) of 21.65 $\pm$ 0.30.

We believe that spectroscopy of the two arcs in A963 would provide the definitive test for the gravitational lens hypothesis. If both arcs have identical redshifts greater than the cluster redshift, it would be hard to appeal to any other mechanism except gravitational lensing for their origin.

If these blue arcs are the result of gravitational lensing, they may be useful for determining the mass of the cores of clusters of galaxies. If the redshift for the background object is measured, it should be possible to obtain a mass estimate of the lensing object. For A963, the lens mass will be of order 10^{13} solar masses unless the redshift of the background object is close to the cluster redshift of 0.2. Obtaining the redshifts of these arcs, though difficult, may provide an estimate of the mass of the core of this cluster of galaxies which can be compared to that determined through the use of mass-to-light ratios or the virial theorem. It is important to take the cluster core into account when modeling the lenses, as its amplifying effects can become quite large.

So far, all three of the known arcs are very blue in color. Are there any "red arcs"? We believe they may exist, but they will be quite faint and exceedingly rare. For E/S0 galaxies at a redshift of 1, the *B* band *K*-correction is approximately 3 mag (Pence 1976). If a red galaxy were being lensed by A963, its arcs would be undetectable, unless the galaxy had an extremely high surface brightness. Using the arcs of A963 as an example, the red galaxy μ_B would have to be 18.3. Such high surface brightness is only found in the core region of E/S0 galaxies. This makes the probability of alignment for the production of arcs very small. It is possible that the cores of E/S0 galaxies have been lensed, but as in the case of QSOs, the images produced are only point sources. Therefore, these images may go unnoticed. For these reasons, it may not be possible to draw strong conclusions about the galaxy population at high redshift using statistics based on "blue arcs."

V. CONCLUSIONS

We have found two blue arcs associated with the cD galaxy in Abell 963. Both arcs are very blue in color and appear to be concentric about the center of the cD. Because of the geometry and the extreme color of the two arcs, we suggest that the arcs are produced by lensing of a background galaxy by the cD and the associated galaxies in the core of Abell 963. A simple lens model, with plausible parameters, reproduces the main features of the arcs.

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REFERENCES

Braun, E., and Dekel, A. 1987, preprint.
Butcher, H., and Oemler, A., Jr. 1984, *Ap. J.*, **285**, 426.
Butcher, H., Oemler, A., Jr., and Wells, D. C. 1983, *Ap. J. Suppl.*, **52**, 183 (BOW).
Coleman, G. D., Wu, C.-C., and Weedman, D. W. 1980, *Ap. J. Suppl.*, **43**, 393.
Einstein, A. 1936, *Science*, **84**, 506.
Fernie, J. D. 1983, *Pub. A.S.P.*, **95**, 782.
Freeman, K. C. 1970, *Ap. J.*, **160**, 811.

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1988ApJ...329L..21L

Grossman, S. A., and Narayan, R. 1988, *Ap. J.* (*Letters*), **324**, L37.
Heasley, J. N., and Christian, C. A. 1986, *Ap. J.*, **307**, 738.
Hlivak, R. J., Henry, J. P., and Pilcher, C. B. 1984, *Proc. Soc. Photo-Opt. Instr. Eng.*, **445**, 122.
Kent, S. M., and Gunn, J. E. 1982, *A.J.*, **87**, 945.
Lavery, R. J. 1988, Ph.D. thesis, University of Hawaii.
Lavery, R. J., and Henry, J. P. 1986, *Ap. J.* (*Letters*), **304**, L5.
———. 1988, *Ap. J.*, **330**, in press.
Leibes, S. 1964, *Phys. Rev. B*, **133**, 835.
Lynds, R., and Petrosian, V. 1986, *Bull. AAS*, **18**, 1014.
Paczyński, B. 1987, *Nature*, **325**, 572.
Pence, W. 1976, *Ap. J.*, **203**, 39.
Refsdal, S. 1964, *M.N.R.A.S.*, **128**, 295.
Soucail, G., Fort, B., Mellier, Y., and Picat, J. P. 1987*a*, *Astr. Ap.*, **172**, L14.
Soucail, G., Mellier, Y., Fort, B., Hammer, F., and Mathez, G. 1987*b*, *Astr. Ap.*, **184**, L7.
Thompson, L. A. 1986, *Ap. J.*, **306**, 384.
Turner, E. L., Ostriker, J. P., and Gott, J. R., III. 1984, *Ap. J.*, **284**, 1.

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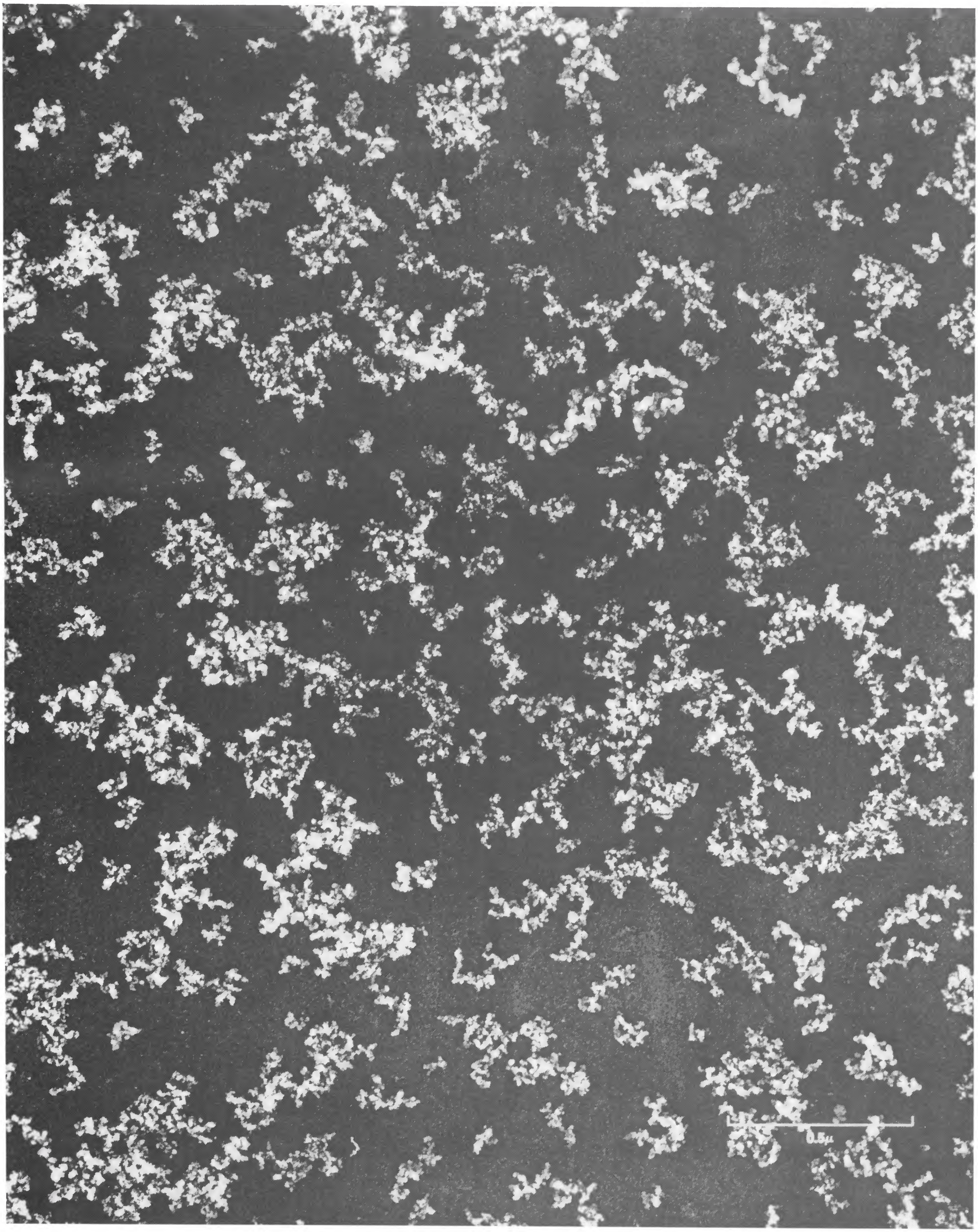

FIG. 1.—Fumed silica clusters. Primary particles are ~ 10 nm. Because of high formation temperature, particles are molten and fuse on contact (courtesy of Cab-0-Sil Division, Cabot Corporation).

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MEAKIN AND DOWN (*see* **329**, L39)