THE ASTROPHYSICAL JOURNAL, **286**: 144–158, 1984 November 1

X-RAY EMISSION FROM M82

M. G. WATSON AND V. STANGER
X-Ray Astronomy Group, University of Leicester
AND
R. E. GRIFFITHS
Harvard-Smithsonian Center for Astrophysics
Received 1983 November 10; accepted 1984 May 4

ABSTRACT

We present an X-ray study of M82 with the *Einstein Observatory* imaging instruments. Observations with the HRI show a luminous, extended X-ray source centered on M82. The most intense feature in the X-ray image has dimensions $\sim 30''$–$60''$ and corresponds quite closely to the optically brightest region near the nucleus of the galaxy. Several discrete unresolved sources are detected in this central region. Outside the central region a diffuse X-ray halo is detected which extends for several arc minutes along the minor axis of the galaxy both north and south of the nucleus. The X-ray halo shows substantial spatial correlation with the Hα filamentary structure within the optical halo. We interpret these results in the context of the current "starburst" models for the nuclear activity in M82, and discuss the importance of the discovery of the X-ray halo in distinguishing between alternative hypotheses for the origin of the optical halo.

Subject headings: galaxies: individual — stars: formation — X-rays: sources

I. INTRODUCTION

The nearby galaxy M82 (NGC 3034) has been a favorite object of study ever since it was proposed as an "exploding galaxy" by Lynds and Sandage (1963). M82 is a nearly edge-on system with inclination $\sim 10°$ at an estimated distance of 3.25 Mpc. The galaxy, classified as Irr II (Sandage 1961) or I0 (de Vaucouleurs and de Vaucouleurs 1964), has approximate optical dimensions $13' \times 8'$, corresponding to a physical size somewhat smaller than our Galaxy. The nuclear region, with dimensions $\sim 50'' \times 15''$ elongated along the plane of the galaxy, is however, considerably larger than the corresponding region of our Galaxy (e.g., Solinger, Morrison, and Markert 1977), and the total radio and infrared luminosities, estimated at $L_R \approx 10^{39}$ ergs s^{-1} and $L_{IR} \approx 10^{44}$ ergs s^{-1} (Hargrave 1974; Rieke *et al.* 1980), are also much greater. Optically and in the near-IR the nuclear region is dominated by high surface brightness star clusters and giant H II regions (e.g., O'Connell and Mangano 1978) often partly obscured by prominent dust clouds. The observed radio and far-infrared emission from M82 is concentrated in the nuclear region, and has a complex, clumpy appearance dominated by a compact nonthermal source 41.9+58, (e.g., Rieke *et al.* 1980; Kronberg, Biermann, and Schwab 1981) which lies $\sim 10''$ from the optical/IR nucleus.

The many unusual features of the nuclear region of M82 have been attributed to a large burst of star formation initiated 10^7–10^8 years ago and possibly still continuing (e.g., O'Connell and Mangano 1978). There is good evidence that this burst of star formation was triggered by a tidal interaction with the nearby galaxy M81 (e.g., Cottrell 1977).

Outside the nuclear region, the galactic disk is relatively normal, but in continuum and Hα plates the appearance of M82 is dominated by an elongated halo which extends for several arcminutes along the minor axis of the galaxy. In Hα the halo has a complex filamentary structure including components with radial and tangential alignments. Spectroscopic measurements reveal radial velocity differences of the order ± 100 km s^{-1} between the filaments to the north and south of the nucleus. This velocity field was originally interpreted as evidence for outflow along the minor axis with space velocities ~ 1000 km s^{-1} (hence the "exploding galaxy" [Lynds and Sandage 1963; Burbidge, Burbidge, and Rubin 1964]). The discovery of significant polarization in the emission lines from parts of the filamentary structure, and the well-ordered pattern of broad-band polarization (Visvanathan and Sandage 1972; Visvanathan 1974; Bingham *et al.* 1976) led Solinger, Morrison, and Markert (1977) to reinterpret the halo as scattering of light from the nuclear regions into the line of sight by dust, thus removing any need to invoke high-velocity outflow from the nucleus. Recent spectroscopic work by Axon and Taylor (1978) (also Axon 1983, private communication) has, however, indicated that outflow may indeed be taking place. This suggestion is also supported by O'Connell and Mangano (1978), who demonstrated that the line emission from the inner regions of the halo is dominated by ionized plasma rather than cool scattering dust.

M82 was the suggested identification for a weak X-ray source appearing in both *Uhuru* and *Ariel 5* catalogs (Forman *et al.* 1978; McHardy *et al.* 1981), and the identification was confirmed by *HEAO 1* modulation collimator observations (Griffiths *et al.* 1979). In this paper we present observations of M82 with the *Einstein Observatory* soft X-ray imaging instruments (for details see Giacconi *et al.* 1979), which, because of their superior angular resolution and sensitivity, allow a detailed study of the X-ray emission from the galaxy.

II. OBSERVATIONS

Einstein observations of M82 were made with both the Imaging Proportional Counter (IPC) and the High Resolution Imager (HRI). The IPC image covers a field $\sim 1°$ square with arc minute spatial resolution and show a bright source coincident with M82. The IPC observation also provides a soft X-ray spectrum of the source with modest energy resolution. The HRI image, with a few arcsec resolution over a $\sim 25'$ field,

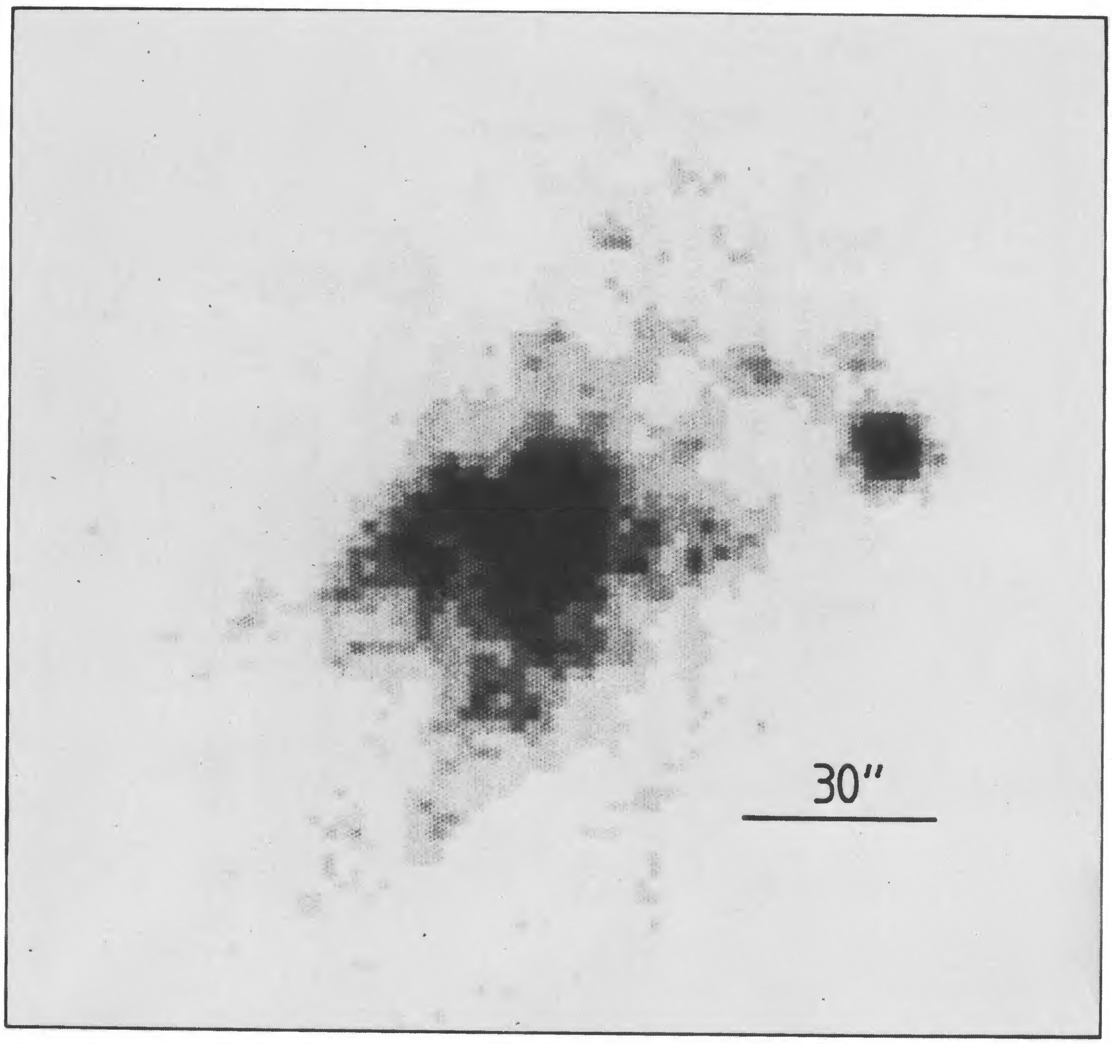

FIG. 1.—Einstein HRI (∼0.2–3.5 keV) X-ray image of M82 with pixel size 2″ displayed on a linear gray scale. The image has been smoothed by cross-correlation with the HRI point response function.

TABLE 1

OVERALL X-RAY MEASUREMENTS OF M82 USING *Einstein Observatory* INSTRUMENTS

Parameter	IPC	MPC	HRI
Total count rate [counts s^{-1}]	0.51 ± 0.01	0.39 ± 0.04	0.16 ± 0.006
X-ray spectrum:			
(i) Thermal:			
kT [keV]	3 (+2, −1.2)	5 (+2, −0)[a]	...
N_H [10^{20} cm^{-2}]	6 (+8, −3)	<40	...
(ii) Power law:			
Alpha[b]	−2.3 (+1, −1)	−2.2 (+0.3, −0.2)	...
N_H [10^{20} cm^{-2}]	21 (+11, −15)	<80	...
Fluxes[c] [ergs cm^{-2} s^{-1}]	1.8×10^{-11} [0.2–4 keV]:	8.5×10^{-12} [2–6 keV]:	2.4×10^{-11} [0.2–4 keV]:
Luminosities[c] [ergs s^{-1}, $D = 3.25$ Mpc]	2.3×10^{40} [0.2–4 keV]:	1.1×10^{40} [2–6 keV]:	2.7×10^{40} [0.2–4 keV]:

NOTE.—Errors quoted in parentheses are approximate 90% confidence interval for 2-parameter spectral fits. For the IPC spectra the errors include appropriate allowance for the uncertainties in detector gain and background subtraction. The errors for the MPC spectral fits are purely statistical and probably underestimate the true uncertainties.

[a] Simple bremsstrahlung plus Gaunt factor spectrum fitted to MPC data.

[b] Photon number index.

[c] Fluxes and luminosities are corrected for an assumed line of sight column density of $N_H = 6 \times 10^{20} cm^{-2}$.

shows a complex emission region centered near the nucleus of the galaxy with significant emission over a region several arc minutes wide (see Fig. 1 and also Fig. 6). Spectral information, in the ~2–15 keV band, is also provided by the data from the Monitor Proportional Counter, a nonimaging instrument co-aligned with IPC and HRI. The IPC observation was made on 1979 April 8–9 with a total exposure time of 4292 s. The HRI observation was made between 1979 May 3 and May 6 with total exposure time 13111 s. In both imaging observations, M82 was very nearly in the center of the field of view.

III. ANALYSIS AND RESULTS

a) X-Ray Spectra

We have used the IPC and MPC data to fit trial X-ray spectra corresponding to thermal and power law forms, in both cases including absorption by cold matter in the line of sight. The results, summarized in Table 1, indicate a relatively low characteristic temperature for thermal emission or correspondingly steep spectral index for power law models (but note that, given the uncertainties in the spectral parameters, we cannot distinguish the X-ray spectrum of M82 from that of most active galaxies which have typical photon number indices $\alpha \approx -1.7$ [e.g., Mushotzky *et al.* 1980; Mushotzky 1982; Holt 1981]), even though the emission processes are probably very different. It is not possible to reject either spectral form statistically since both give acceptable fits. The best-fit column densities have a wide range and differ according to which model is chosen. The acceptable range of column densities is further restricted to the range $\sim 3 \times 10^{20}$ to 2×10^{21} cm^{-2} by using the total HRI count rate as an additional constraint on the spectral shape. In order to calculate X-ray fluxes and luminosities, a thermal spectrum with $kT = 3$ keV and $N_H = 6 \times 10^{20}$ cm^{-2} has been assumed. (The derived fluxes and luminosities are particularly sensitive to larger values of N_H; for $N_H = 2 \times 10^{21}$ cm^{-2} the values are increased by ~30%.) With the assumed values, the HRI flux and luminosity are slightly higher than for the IPC. This may imply a composite X-ray spectrum for M82 with one component (e.g., the halo discussed below) having a softer (and/or less cut off) spectrum. The reddening in the direction of M82, estimated from the $E(B-V)$ maps of Burstein and Heiles (1982) is $A_v \approx 0.1$ mag, corresponding to $N_H \approx 2.5 \times 10^{20}$ cm^{-2} using the calibrations of Jenkins and Savage (1974), and Seaton (1979). The best-fit N_H for both model spectra (and our assumed value) is somewhat higher, probably indicating some X-ray absorption within M82 itself. Star clusters within the nuclear region of M82 have been found to exhibit optical extinction as high as $A_v = 5$ mag. Although X-ray emission from the clusters themselves is likely to make up only a fraction of the total X-ray flux, we cannot rule out the possibility that major sources of X-ray emission within M82 also suffer an equivalent amount of optical extinction, corresponding to 5×10^{21}–10^{22} H atoms cm^{-2}. This would lead to higher values for the X-ray luminosity of individual sources.

b) X-Ray Morphology

The HRI X-ray image of M82 (Figs. 1 and 2, see also Fig. 6) appears to show two separate components: (i) a complex central region containing several local maxima in X-ray surface brightness over a region ~1′ in extent; (ii) a halo of patchy, diffuse X-ray emission extending several arcminutes along the minor axis of the galaxy both north and south of the nuclear region. Detailed examination of the IPC data also reveals the presence of this extended diffuse halo. The "clumpy" appearance of the HRI image indicates that the X-ray emission from the central regions of M82 is dominated by a small number of unresolved, discrete sources which may be either true point sources or bright knots in the emission with scale sizes of the same order as the HRI point response function (i.e., $\lesssim 3''$). We have analyzed the HRI image using an algorithm which utilizes a cross-correlation technique to locate possible unresolved (i.e., "point") sources in the presence of a nonuniform diffuse emission component (for more details see Watson *et al.* 1981). Eight unresolved sources are found by this technique above a 5 σ significance threshold. Seven of these are embedded in the

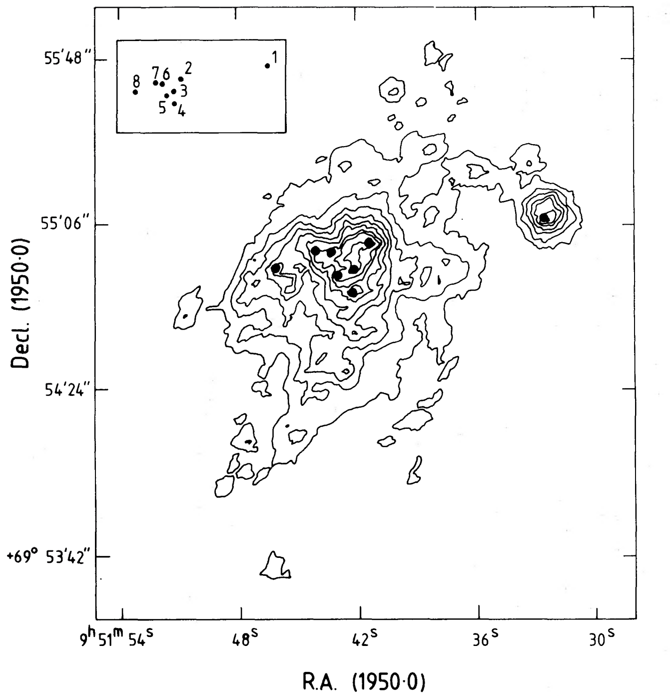

FIG. 2.—Contour map of Fig. 1. Contour levels are plotted with a linear interval of $\sim 3.8 \times 10^{-6}$ HRI counts s^{-1} arcsec^{-2}, corresponding to 3.5 σ. The lowest contour level corresponds to $\sim 7.6 \times 10^{-6}$ HRI counts s^{-1} arcsec^{-2}, approximately 7 σ above background. The unresolved sources discussed in the text are shown as filled circles. The inset shows the reference numbers used in Table 2.

bright central region, and the eighth lies $\sim 1'$ to the west. Their positions, approximate count rates, and luminosities are listed in Table 2 (see also Fig. 2). The unresolved sources have soft X-ray luminosities (assuming the same spectral parameters as above) in the range 5–10 $\times$ 10^{38} ergs s^{-1} if they lie in M82.

In Figure 3 we show profiles of the X-ray surface brightness through the center of M82 in two orthogonal directions corresponding to the major and minor axes of the galaxy. These profiles clearly show the presence of the diffuse X-ray halo extending along the minor axis out to $\sim 3'$ in the SE and $\sim 1'.7$–$2'.5$ in the NW, whereas along the major axis the half-width of the detectable emission is $\lesssim 1'.4$. The halo seen in the HRI is clearly not separate from the bright central region; indeed the halo merges into the central emission at smaller distances from the nucleus. There is some indication of a change in gradient of the surface brightness profile along the minor axis (Fig. 3*a*) at radii between $\sim 30''$ (NW side) and $\sim 60''$ (SE side). For the purpose of discussion we define the "nuclear region" to be inside a 30" radius and the "halo" to be the region outside 30". In Table 2, count rates and luminosities are quoted for the nuclear region and for the halo. The X-ray halo, although of low surface brightness, accounts for $\gtrsim 50\%$ of the X-ray flux from M82 in the HRI energy band. Values are also quoted for a small region near the X-ray emission peak which includes sources 2 and 3 and the position of the compact radio source 41.9+58. The seven point sources in the nuclear region contribute a large fraction ($\sim 50\%$) of the flux within 30" of the nucleus (see also notes to Table 2). The remaining flux could either be associated with a truly diffuse component, or be due to a population of weaker point sources which are not individually resolved in the HRI observation.

c) Identification of Unresolved X-Ray Sources

We have looked for possible identifications for the unresolved X-ray sources listed in Table 2 using the positions of optical features (star clusters, H II regions) from Kronberg *et al.* (1972) and O'Connell and Mangano (1978) and the positions of compact radio features given by Kronberg and Wilkinson (1975). Given the high source density in the radio and optical bands, the chance association rate must be quite high. Nevertheless, we list in Table 2 possible identifications with features

TABLE 2
X-RAY SOURCES WITHIN M82

Component	R.A.[a]	Decl.	I_x[b]	L_x[c]	Comments[d]
	(1950.0)				
1	$9^h51^m32^s.4$	69°55'07"	4.4	8×10^{38}	$\sim 1'$ W of nuclear region
2	9 51 41.3	69 55 01	5.4	9×10^{38}	41.4+59 2" S; OM E 2".3 E.
3	9 51 42.1	69 54 55	5.1	9×10^{38}	41.9+58 3" N; OM C 2" SW.
4	9 51 42.1	69 54 49	4.0	7×10^{38}	
5	9 51 42.9	69 54 53	4.4	8×10^{38}	
6	9 51 43.3	69 54 59	4.3	7×10^{38}	43.1+60 1".5 NW; KPV A 3" SE.
7	9 51 44.0	69 54 59	3.7	6×10^{38}	44.0+60 1".5 N; OM A (nucleus?) 1" NW.
8	9 51 46.0	69 54 55	2.9	5×10^{38}	
Peak region	9 51 41.7	69 54 58	7.3	1.2×10^{39}	Region 10" × 12", includes 41.9+58.
Nuclear region	...	...	43.7	7.4×10^{39}	$R < 30''$
X-ray halo	...	...	116.4	2.0×10^{40}	$30'' < R < 300''$
Total	...	...	160.1	2.7×10^{40}	

[a] Errors in positions of the unresolved sources are dominated by the systematic uncertainty in satellite attitude. 90% confidence radius is $\sim 4''$ in both coordinates.

[b] Background subtracted HRI count rates [$\times 10^{-3}$ counts s^{-1}]. For the unresolved sources the intensities are equivalent point source values, for other components the values are directly measured for the regions specified, and hence slightly underestimate the true flux because the HRI point response function has broad wings. This is not an important effect for extended emission regions. Because the wings of the HRI are broad, some of the unresolved sources effectively overlap and hence "share" flux. In consequence the contribution of the point sources to the total flux seen in the central region is not simply given by the sum of the values for each source.

[c] Soft X-ray luminosities (ergs s^{-1}; 0.2–4 keV) assuming spectral parameters quoted in text.

[d] Possible identifications with radio and optical features within 3" radius (see text). aa.a + bb notation = Kronberg and Wilkinson 1975; OM = O'Connell and Mangano 1978; KPV = Kronberg *et al.* 1972.

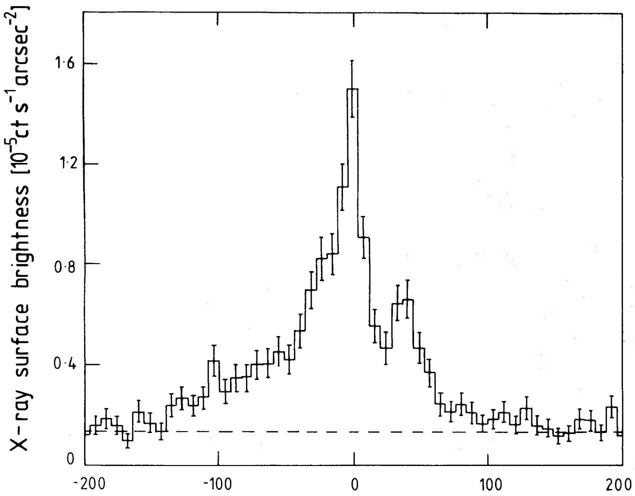

FIG. 3*a*

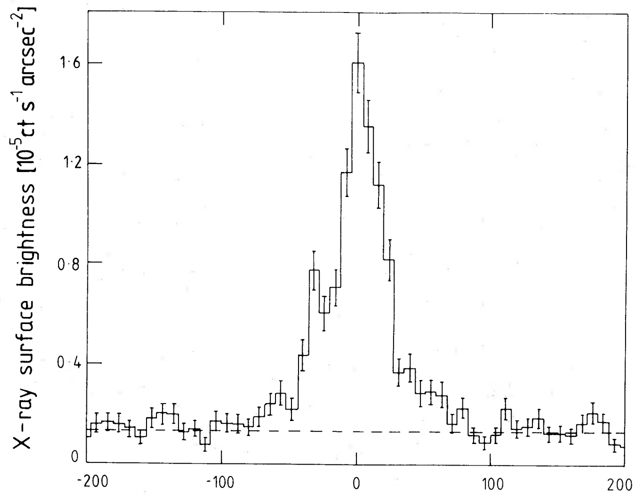

FIG. 3*b*

FIG. 3.—Cuts through M82 in two orthogonal directions. The value in each histogram bin is the average X-ray surface brightness integrated across a strip 2′ wide. (*a*) profile at p.a. 150° (i.e., SE to NW along minor axis of galaxy); (*b*) profile at p.a. 60° (i.e., NE to SW along major axis of galaxy). Background levels are indicated by the dashed lines.

lying within 3″ of the X-ray positions. Two particularly interesting associations are apparent:

i) source 7 lies within $\sim 1''$ of star cluster A of O'Connell and Mangano. (This is probably the same as cluster E of Kronberg *et al.* 1972.) O'Connell and Mangano associate cluster A with the nucleus of M82. This also agrees with the position of the 2.2 μm nucleus given by Rieke *et al.* 1980. Thus source 7 could be the nuclear X-ray source of the galaxy. If this is the case, the X-ray luminosity quoted in Table 2 would probably be an underestimate, since optical and IR studies have revealed very high local absorption in the vicinity of the nucleus.

ii) Although the compact radio source 41.9+58 is not coincident with any of the unresolved X-ray sources, it lies very close to the peak of the X-ray emission, midway between sources 2 and 3, along a ridge which is more or less aligned with the minor axis of M82. This raises the intriguing possibility that we are seeing an extended feature associated with the compact radio source (see § IV). We estimate the HRI luminosity of any *point* source coincident with 41.9+58 to be $L_x \lesssim 3 \times 10^{38}$ ergs s^{-1}.

Source 1 lies completely outside the nuclear region in the halo of M82. (Note that analysis of the radial surface brightness profile of source 1 shows it to be completely consistent with a point source.) No optical counterpart to source 1 is visible on available plate material; the magnitude limit derived from a deep CCD plate obtained by J. Stocke is $m_R \gtrsim 22.5$ (this limit being set by the presence of diffuse light from the halo of M82), giving an implied X-ray to optical flux ratio of $f_x/f_{\rm opt} \gtrsim 200$. (This value is uncertain because of unknown reddening and bolometric corrections.) Such an extreme flux ratio has been observed only for low-mass, Population II X-ray binaries (e.g., Patterson 1981). We do not favor the alternative possibility of identification with a background QSO with anomalously high reddening since none of the QSOs identified in the *Einstein* Medium and Deep surveys (e.g., Stocke *et al.* 1983; Griffiths *et al.* 1983) has shown such an extreme ratio. Source 1 must therefore be a very luminous low-mass X-ray binary located in the halo of M82. Its soft X-ray luminosity exceeds that of any established (or putative) system in our Galaxy, none of which has 2–10 keV luminosities above $\sim 2 \times 10^{38}$ ergs s^{-1} (e.g., Bradt and McClintock 1983). Several other very luminous unresolved sources have been observed in other nearby galaxies (e.g., Long and van Speybroeck 1983), but most of these lie in the outer regions of normal spirals. This source, if in M82, may be of particular interest as a possible Population II system lying in the halo region of the galaxy.

The alternative interpretation, that the source is a foreground object, can probably be ruled out, since in order for it to be within our Galaxy, i.e., within ~ 10 kpc, its intrinsic luminosity would have to be $L_x \lesssim 8 \times 10^{33}$ ergs s^{-1}, two to three orders of magnitude lower than any known low-mass X-ray binary. In addition, the optical luminosity distribution for low-mass X-ray binaries is quite narrow (mean value $M_v \approx 1$: van Paradijs and Verbunt 1981); thus on this basis its implied distance is $\gtrsim 100$ kpc, well outside our Galaxy.

The relative X-ray source positions are determined to $\lesssim 1''$, but are subject to an additional systematic error of $\sim 4''$ (90% confidence) arising from the uncertainty in the absolute pointing axis of the *Einstein* telescope. Any definite identification of an individual X-ray source could be used to refine the remaining X-ray source positions. In the absence of such an identification it should be noted that only a few of the associations listed in Table 2 are likely to be correct since the position differences range from 0″.5 to 3″ in random directions.

IV. DISCUSSION

a) The Nuclear Region

In Figures 4 and 5 we compare the HRI X-ray image of M82 with radio (8 GHz) and optical maps of the galaxy. The X-ray image shows very little similarity with the high-frequency radio map. The radio emission is strongly concentrated in a narrow strip more or less aligned with the plane of the galaxy, whereas the X-ray emission shows a much wider distribution along the minor axis. A number of authors have pointed out the possibility of producing high X-ray luminosities in M82 by inverse Compton scattering of IR photons with the relativistic electrons associated with the nonthermal radio emission from the nuclear region (e.g., Hargrave 1974; Rieke *et al.* 1980). The predicted X-ray luminosity from this process is $\sim 10^{40}$ ergs s^{-1}. Because of the complete lack of correlation between X-ray and radio morphologies we suggest that inverse Compton X-ray emission is not the dominant mechanism in M82; this may be the case because the ambient magnetic field is somewhat higher than the equipartition value, since the inverse Compton flux varies as $B^{-(1+\alpha)}$, where α is the low-frequency radio spectral index (≈ 0.3, Hargrave 1974). Indeed, the only way of understanding the X-ray morphology if the bulk of X-ray emission had an inverse Compton origin would be to hypothesize a remarkably different spatial distribution for the relativistic particles responsible for the X-rays (i.e., those with $\gamma \sim 100$) from that inferred for the particles giving the high-frequency radio emission (which have $\gamma \sim 10^3$–10^4).

The nature of the compact nonthermal radio source 41.9+58 is still the subject of some debate (e.g., Kronberg, Biermann, and Schwab 1981). Kronberg *et al.* discuss three possible models for 41.9+58: that it is the true nucleus of M82, that it is an energetic SNR, or that it is a luminous young pulsar (embedded in a SNR). In all three cases the radio emission is likely to be synchrotron in origin, and a naive extrapolation of the spectrum with the measured index $\alpha = -1.0 \pm 0.2$ (Kronberg and Wilkinson 1975) to the X-ray band yields a predicted X-ray luminosity L_x (0.5–4.5 keV) $\approx 10^{36}$–10^{39} ergs s^{-1}. Thus the lack of an unambiguous detection of 41.9+58 at X-ray wavelengths is completely consistent with the spectral extrapolation. In order for 41.9+58 to be detectable in the HRI observations, the spectral index would have to be ~ 0.85 (or flatter) with no break in the spectrum between radio and X-ray wavelengths.

Comparison of the X-ray image with an *R*-band CCD exposure (Fig. 5) shows that there is significant correlation with the optical emission from the central regions of M82. (Also note the absence of X-ray emission from the part of the galaxy bisected by the broad dust clearly visible in Fig. 5. This may be due to strong attenuation of the X-ray emission by the large column density associated with the dust lane.) This immediately suggests that the bulk of the X-ray emission from the nuclear region is of Population I origin, since it is well established that the optical light is dominated by early-type stars, H II regions, etc., as a result of a recent burst of star formation in the galaxy (e.g., O'Connell and Mangano 1978). Although the optical light from the nuclear regions is instrinsically quite blue, the *R*-band image shows the distribution of this optical emission equally well because of the effects of local extinction.

Given the enhanced Population I content and activity of the nuclear regions of M82, it seems most likely that the bulk of the X-ray emission is associated with Population I objects. The possibilities are:

i) *High-mass X-ray binaries.*—These systems have typical luminosities $L_x \approx 10^{35}$–10^{37} ergs s^{-1} in our Galaxy and up to 10^{39} ergs s^{-1} in the Magellanic Clouds (Bradt *et al.* 1983; Clark *et al.* 1978). (Low-mass X-ray binaries, which dominate the nuclear bulge regions of both our Galaxy and M31, have luminosities up to $\sim 10^{38}$ ergs s^{-1}; e.g., Bradt and McClintock 1983; van Speybroeck *et al.* 1979; Vader *et al.* 1982.)

ii) *Supernova remnants.*—SNRs have $L_x \approx 10^{33}$–10^{36} ergs s^{-1} in our Galaxy, but somewhat higher luminosities in the Magellanic Clouds (Long and Helfand 1979; Seward and Mitchell 1981).

iii) *Early-type (i.e., OB) stars.*—The soft X-ray luminosities associated with surface activity in these stars reach $L_x \approx 10^{33}$ ergs s^{-1} (e.g., Vaiana *et al.* 1981).

The discrete X-ray sources detected in M82 (§ III*c*) have such high luminosities, if they are single objects, that they can be plausibly identified only with individual luminous, high-mass X-ray binaries. If this is the case, the much higher incidence of such systems than is found in our Galaxy is in accord with the enhanced star formation rate, and consequent overabundance of massive young stars, in the nuclear region. Note that this explanation requires that these sources have *soft* X-ray luminosities above the Eddington limit for a solar-mass accreting compact object. This need not be a fatal objection since several sources in the Magellanic Clouds also have super-Eddington luminosities (e.g., Clark *et al.* 1978), and the solar-mass Eddington limit can be exceeded in a number of ways (e.g., abundance affects, anisotropic emission, or trivially by raising the mass of the compact object). (The alternative, that these sources are low-mass, Population II binaries, as might be expected by analogy with the equivalent bulge regions of our Galaxy or M31, would imply that the content of this type of binary in M82 was similar to that seen in our Galaxy or M31. This can probably be discounted if the Population II content is proportional to total galactic mass, because M82 has a much lower mass.)

The possibility also exists that some of the discrete sources detected in M82 might be associated with compact star clusters. The most luminous star clusters in M82, regions A and C of O'Connell and Mangano (1978), have estimated total masses $\sim 10^7\ M_\odot$ and mass-to-light ratios indicating that they are dominated by massive young stars. Thus it is possible that the X-ray emission from these regions could be due to the integrated emission from the 10^5–10^6 stars in each cluster, giving total soft X-ray luminosities 10^{38}–10^{39} ergs s^{-1}. A significant fraction of the total X-ray luminosity from the nuclear region of M82 is not resolved into discrete sources in the HRI observation. Although this component could be truly diffuse in origin, it seems much more likely that it is due to a population of weaker discrete X-ray emitters. X-ray binaries, SNRs, and OB stars may all make a contribution. Young SNRs may be particularly important if their average X-ray luminosities are higher because of the greater density of the ISM, as has been suggested by Rieke *et al.* (1980). Indeed, all the nuclear X-ray luminosity of M82 could be explained by SNRs with $L_x = 10^{37}$ ergs s^{-1} and lifetimes equal to 3000 years if the supernova rate is ~ 0.3 per year, as might be expected in a region dominated by a high density of Population I stars. *Individual* SNRs probably have X-ray luminosities too low to be detected in the HRI observation, and indeed none of the compact radio features discussed in § III*c*, many of which may be young SNRs, have convincing X-ray counterparts.

Thus, it seems likely that the nuclear region of M82 is very different from the equivalent bulge region of our Galaxy, or of M31, in being dominated by the emission from Population I objects. Our interpretation finds general support from the recent work of Fabbiano, Feigelson, and Zamorani (1982), who have investigated the X-ray properties of a sample of 33 peculiar galaxies. Fabbiano *et al.* find overall correlations between both *B*-band and radio fluxes with total X-ray flux which they believe can be understood in terms of enhanced star formation rates resulting in increased Population I content of the galaxies.

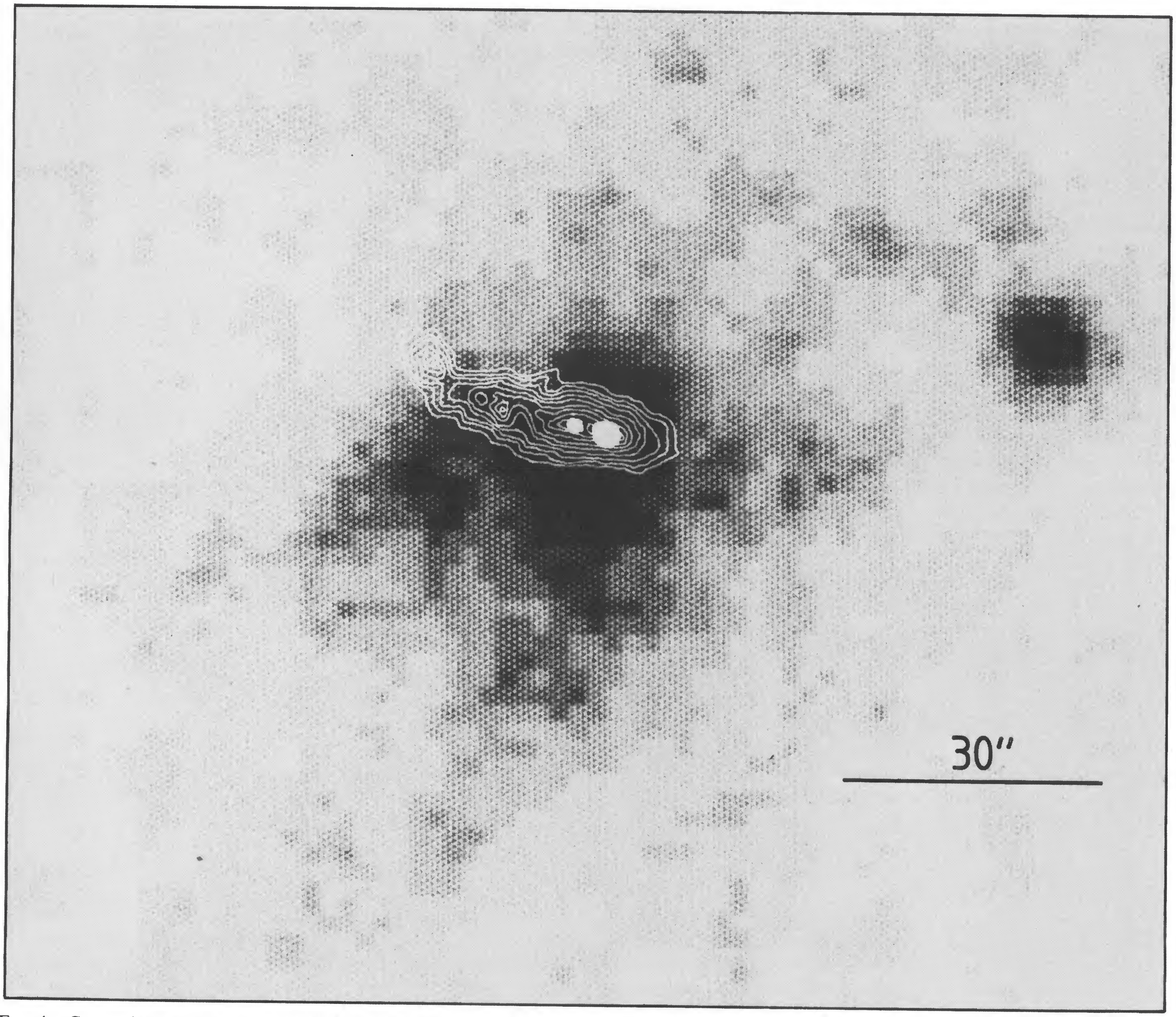

FIG. 4.—Composite radio/X-ray map of M82. Details of X-ray map image as for Fig. 1. Radio contours are schematic and are based on the 8085 MHz map of Kronberg and Clarke (1978) which has 2″.2 resolution.

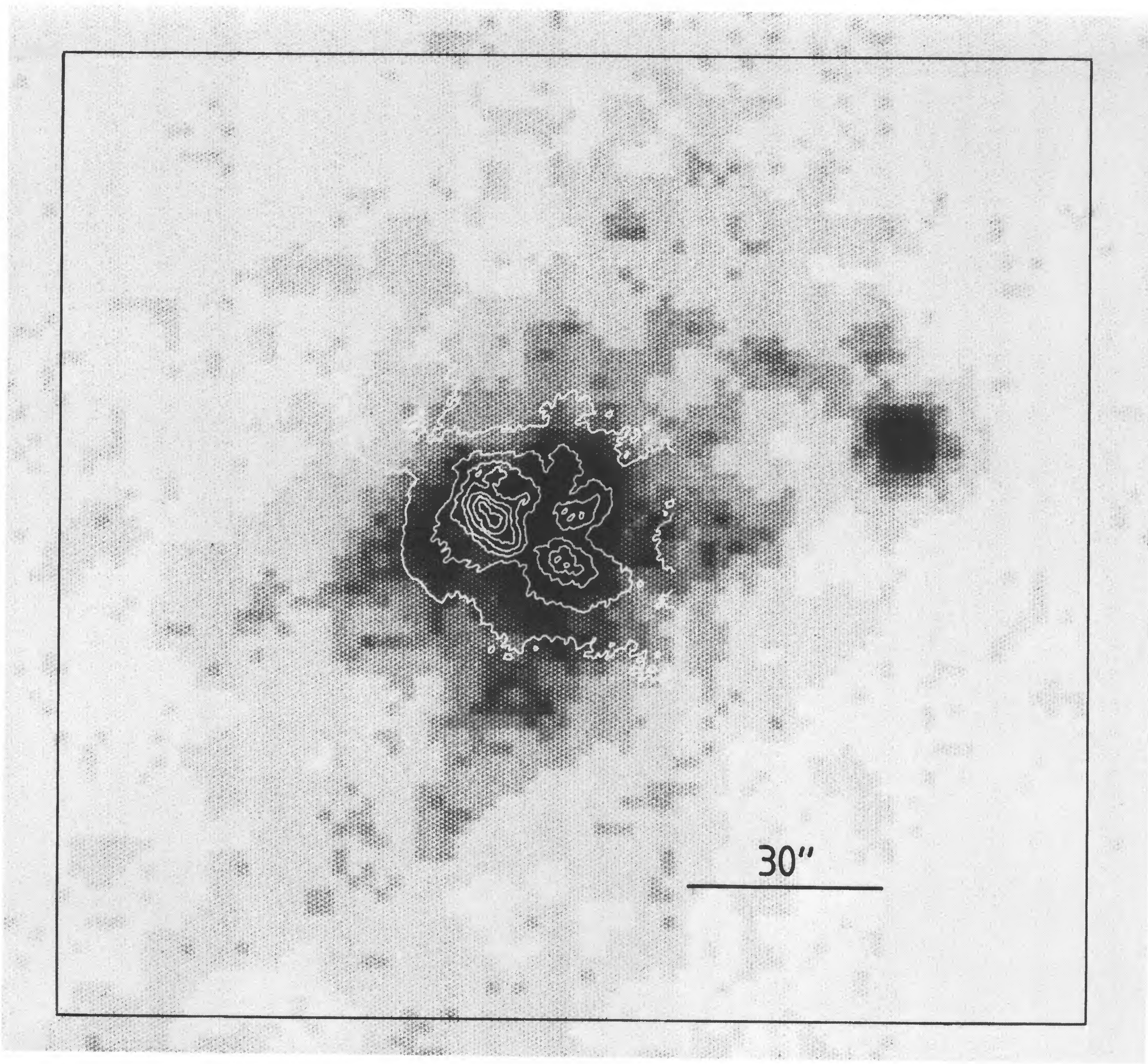

FIG. 5.—Composite optical/X-ray map of M82. Details of X-ray map image as for Fig. 1. Optical contours shown are based on a 4 minute *R*-band CCD observation made by J. Huchra and A. Lawrence using the Mount Hopkins 24 inch (61 cm) telescope.

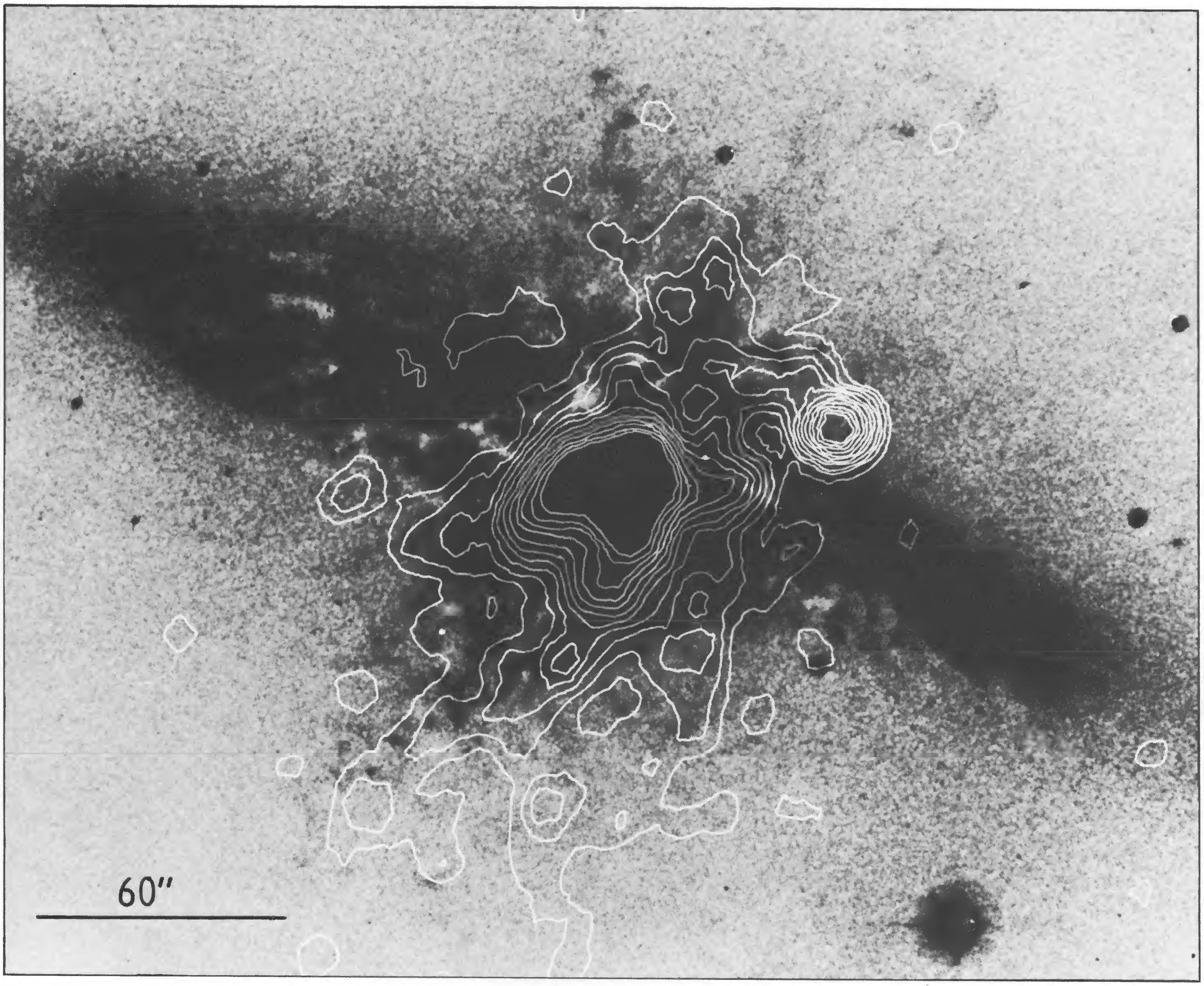

FIG. 6.—Composite Hα/X-ray map of M82. The X-ray image (shown in contour form) has 4″ pixel size and has been smoothed by cross-correlation with a 2D Gaussian function with $\sigma = 4''$. The lowest contour is well above the background level; the interval between the contour levels is $\sim 2.5\ \sigma$. The Hα photograph is taken from Lynds and Sandage (1963).

b) The X-Ray Halo

In Figure 6 the X-ray image is compared with a deep Hα plate of M82. The X-ray and optical halos have similar dimensions, and both extend farther to the SE than to the NW. There is also some significant correlation between the X-ray halo and the optical filamentary structure, strongly suggesting some physical connection between the two. We have also compared the X-ray data with a high-quality Hα plate kindly supplied by D. Axon and find additional correlation with features not apparent on the Lynds and Sandage plate. The X-ray halo is unlikely to arise from a nonthermal process since the nonthermal radio flux from the halo region is a small fraction of the total (e.g., Hargrave 1974), implying relativistic particle densities too low to give the observed X-ray flux by either synchrotron or inverse Compton mechanisms even if the required energy densities in magnetic field or photons were available. This conclusion would of course be invalid if the relativistic particles with the required energies ($\gamma \approx 100$ for inverse Compton scattering of IR photons or $\gamma \approx 10^7$ for synchrotron emission) had substantially different spatial distributions and energy densities from those particles responsible for the radio emission. We believe the X-ray emission from the halo is therefore almost certainly due to thermal emission from hot gas ($T \approx 10^7$ K).

Using the profiles shown in Figure 3, we have estimated the full extent of the halo, and hence the halo volume. Assuming the halo thickness along the line of sight is equal to the width of the halo, we estimate the total volume to be $V_{\rm halo} \approx 6 \times 10^{65} f$ cm^3, where f is the volume filling factor. Because of the patchiness of the halo X-ray emission, we assume $f = 0.1$, although lower values clearly cannot be ruled out (especially if the halo is thin along the line of sight). For an isothermal plasma with $T \approx 10^7$ K and total luminosity $L_x \approx 2 \times 10^{40}$ ergs s^{-1}, the required emission measure is $\sim 2.6 \times 10^{63}$ cm^{-3}, giving a mean number density $\langle n_e \rangle \approx 0.2$ cm^{-3}, total emitting mass $M_{\rm tot} \approx 10^7$ $M_\odot$, and total thermal energy content $E_{\rm th} \approx 6 \times 10^{55}$ ergs. The radiative lifetime of this plasma is $\sim 10^8$ years.

The existence of such a hot extended halo in M82 poses several interesting questions:

i) What is the origin of the halo, and what is the energy supply to heat the gas?

ii) Is the halo bound to the galaxy, or is it escaping as a wind?

iii) How are the X-ray and optical halos related?

The general properties of hot galactic halos or coronae have been discussed by many authors (e.g., Bregman 1978, 1980; York 1982 and references therein). In many respects the halo observed in M82 resembles the models discussed by Bregman (1980), but with one clear difference in that the M82 halo is localized to a region near the minor axis whereas Bregman's models (and most previous work) involve halos which extend to large scale-heights over the entire galactic disk. This difference can easily be understood if the M82 halo is linked to star formation occurring in the galaxy. Since enhanced stellar activity in M82 is strongly concentrated to the nuclear region, the X-ray halo would then be expected to show a similar concentration. To be more specific, we suggest that the halo is heated by supernovae occurring within the nuclear region (cf. McKee and Ostriker 1977; Bregman 1978, 1980). This is quite plausible since, if the energy release per supernova is 10^{51} ergs and the supernova rate is 0.2 yr^{-1} over a time scale 10^7 years, only 2% of the total energy release from supernovae is needed to explain the observed X-ray halo.

The escape velocity within the halo of M82, inferred from the total galaxy mass $M_{\rm tot} \approx 10^{10}$ $M_\odot$ (e.g., Cottrell 1977), is $\sim$200–300 km s^{-1}. This implies that a halo with temperature $T \gtrsim 2 \times 10^6$ K would not be bound to the galaxy and would escape as a wind on a time scale 10^6–10^7 years, assuming a scale size for the halo of 2 kpc. We have no direct way of measuring the halo temperature from the X-ray data, but we require $T_{\rm halo} > 10^6$ K for it to be observed with the HRI in the presence of a column density $N_{\rm H} > 3 \times 10^{20}$ cm^{-2} (the comparison of the IPC and HRI fluxes suggests $T_{\rm halo} < 3 \times 10^7$ K). Thus it seems quite possible that the halo is hot enough to be unbound.

At present there are two more or less contradictory views on the nature of the optical halo and filaments in M82 (see § I): either it is line-emitting gas outflowing with velocities 400–600 km s^{-1} (Axon and Taylor 1978; Axon, private communication 1983—note this velocity is somewhat lower than the values originally found by Lynds and Sandage 1963), or it could arise from slowly moving cold dust which scatters optical light originating in the nuclear region into our line of sight (e.g., Solinger, Morrison, and Markert 1977). The presence of dust in the same region as the hot X-ray plasma is difficult to understand unless the halo region is highly inhomogeneous, or unless the dust is continuously supplied from outside the halo, since the time scale for destruction of dust grains within a 10^7 K plasma is short. In contrast, if the filaments are line-emitting regions with substantial velocities with respect to the nucleus of M82, the good correlation between the halo X-ray emission and the filamentary structure can perhaps be plausibly explained by analogy with galactic SNRs.

X-ray emission from SNRs originates in shock-heating of the ISM as the shell moves out with velocities $\sim 10^2$–10^3 km s^{-1}. Hα filaments form in older SNRs (e.g., Cygnus Loop, IC 443) when radiative losses lead to rapid cooling and hence fragmentation of the denser parts of the shock front (e.g., Cox 1972). This can lead to overall correlation between X-ray and optical filament morphologies since X-ray emission is also being produced near the shock boundary. We envisage that a similar mechanism may be taking place in the M82 halo, although the difference between the optical spectra and morphology of the M82 filaments and those observed in SNRs suggests that this analogy may have only limited validity. The complex morphology of the M82 halo in this interpretation is then a direct result of the very complex velocity field of the outflowing gas, for which there is ample evidence from spectroscopic studies (Axon, private communication 1983). Thus we believe that the detection of an X-ray halo adds strong support to the contention that the inner parts of this halo are dominated by hot gas flowing out from the nuclear region. The evidence for the presence of large amounts of dust, especially in the outer halo, is, however, overwhelming. This can be reconciled with the presence of the X-ray halo most naturally if the X-ray emitting gas and cold dust occupy spatially distinct regions. Our conclusions regarding the importance of outflow in the inner halo are broadly similar to those reached by Williams, Caldwell, and Schommer (1984) on the basis of their recent imaging spectral study of ionized hydrogen in M82. Williams *et al.* also find evidence for an accretion flow *onto* M82, as well as gas in polar orbits about the galaxy. Clearly the dynamics of gas in the vicinity of M82 must be highly complex.

V. SUMMARY

The main conclusions of this X-ray study of M82 with the *Einstein* imaging instruments are:

i) The X-ray emission from M82 is not dominated by a single "nuclear" source as is the case for many active galaxies. X-ray emission is detected from a large region centered near the nucleus with overall dimensions $\sim$0.5–1 kpc. Several discrete sources are detected within this nuclear X-ray emission region which have luminosities $\sim 5\text{–}10 \times 10^{38}$ ergs s^{-1} if located in M82. One of these discrete sources may be associated with the optical/IR nucleus of M82. A ridge of emission near the peak of the X-ray surface brightness may possibly be an extended feature associated with the compact radio source 41.9+58.

ii) On larger scales we have detected a diffuse X-ray halo aligned along the minor axis of the galaxy which extends for several kiloparsecs both north and south of the nuclear region. This X-ray halo is well correlated with the Hα filamentary structure of the optical halo.

The nuclear component of the X-ray emission can most easily be understood in terms of the integrated emission from Population I objects such as massive X-ray binaries, SNRs, and OB stars (several of the point X-ray sources may be individual luminous binaries). This possibility exists because of the enhanced Population I content of the nuclear region arising from an intense burst of star formation occurring 10^7–10^8 years ago. The same "starburst" activity (particularly supernova explosions) may also have given rise to mass outflow from the nuclear region which manifests itself as the X-ray halo: a 10^7 K thermal plasma shock-heated by the outflow. If this interpretation is correct, the detection of an X-ray halo is important in enabling us to distinguish between this "expulsion" hypothesis and the dust-scattering interpretation for the optical halo, and it has important implications for our understanding of the dynamics of the gas flows in the vicinity of this most unusual galaxy.

We would like to thank many colleagues at Leicester and CfA, particularly Martin Elvis and Pepi Fabbiano, for much help and advice; John Stocke for obtaining deep CCD plates of the region near source 1; David Axon, Andrew King, Eric Feigelson, and Steve Kahn for several stimulating discussions; and Andrew Lawrence and John Huchra for allowing us to use their CCD data. M. G. W. and V. S. thank the High Energy Division of CfA for their hospitality whilst much of this work was carried out. M. G. W. and V. S. acknowledge financial support from the SERC.

REFERENCES

Axon, D. J., and Taylor, K. 1978, *Nature*, **274**, 37.
Bingham, R. C., McMullen, D., Pallister, W. S., White, C., Axon, D. J., and Scarrott, S. M. 1976, *Nature*, **259**, 463.
Bradt, H. V., and McClintock, J. E. 1983, *Ann. Rev. Astr. Ap.*, **21**, 13.
Bregman, J. N. 1978, *Ap. J.*, **224**, 768.
———. 1980, *Ap. J.*, **237**, 681.
Burbidge, E. M., Burbidge, G., and Rubin, V. C. 1964, *Ap. J.*, **140**, 942.
Burstein, D., and Heiles, C. 1982, *A.J.*, **87**, 1165.
Clark, D. H., Doxsey, R., Li, R., Jernigan, J. G., and van Paradijs, J. 1978, *Ap. J. (Letters)*, **221**, L37.
Cottrell, G. A. 1977, *M.N.R.A.S.*, **178**, 577.
Cox, D. P. 1972, *Ap. J.*, **178**, 143.
de Vaucouleurs, G., and de Vaucouleurs, A. 1964, *Reference Catalogue of Bright Galaxies* (Austin: University of Texas Press).
Fabbiano, G., Feigelson, E., and Zamorani, G. 1982, *Ap. J.*, **256**, 397.
Forman, W., *et al.* 1978, *Ap. J. Suppl.*, **38**, 357.
Giacconi, R., *et al.* 1979, *Ap. J.*, **230**, 540.
Griffiths, R. E., Johnson, M. D., Schwartz, D. A., Schwarz, J., and Blades, J. C. 1979, *Ap. J. (Letters)*, **230**, L21.
Griffiths, R. E., *et al.* 1983, *Ap. J.*, **269**, 375.
Hargrave, P. J. 1974, *M.N.R.A.S.*, **168**, 491.
Holt, S. S. 1981, in *X-ray Astronomy with the Einstein Satellite*, ed. R. Giacconi (Dordrecht: Reidel), p. 173.
Jenkins, E. B., and Savage, B. D. 1974, *Ap. J.*, **187**, 243.
Kronberg, P. P., Biermann, P., and Schwab, F. R. 1981, *Ap. J.*, **246**, 751.
Kronberg, P. P., and Clarke, J. N. 1978, *Ap. J. (Letters)*, **224**, L51.
Kronberg, P. P., Pritchet, C. J., and van den Bergh, S. 1972, *Ap. J. (Letters)*, **173**, L47.
Kronberg, P. P., and Wilkinson, P. M. 1975, *Ap. J.*, **200**, 430.
Long, K. S., and Helfand, D. J. 1979, *Ap. J. (Letters)*, **235**, L77.
Long, K. S., and van Speybroeck, L. P. 1983, preprint (Columbia Astrophysics Lab. Contribution No. 215).
Lynds, C. R., and Sandage, A. R. 1963, *Ap. J.*, **137**, 1005.
McHardy, I. M., *et al.* 1981, *M.N.R.A.S.*, **197**, 893.
McKee, C. F., and Hollenbach, D. J. 1980, *Ann. Rev. Astr. Ap.*, **18**, 219.
McKee, C. F., and Ostriker, J. P. 1977, *Ap. J.*, **218**, 148.
Mushotzky, R. F. 1982, *Ap. J.*, **256**, 92.
Mushotzky, R. F., Marshall, F. E., Boldt, E. A., Holt, S. S., and Serlemitsos, P. J. 1980, *Ap. J.*, **235**, 361.
O'Connell, R. W., and Mangano, J. J. 1978, *Ap. J.*, **221**, 62.
Patterson, J. 1981, *Nature*, **292**, 810.
Rieke, G. H., Lebofsky, M. J., Thompson, R. I., Low, F. J., and Tokunaga, A. T. 1980, *Ap. J.*, **238**, 24.
Sandage, A. R. 1961, *The Hubble Atlas of Galaxies* (Washington, DC: Carnegie Institution of Washington).
Seaton, M. J. 1979, *M.N.R.A.S.*, **187**, 785.
Seward, F. D., and Mitchell, M. 1981, *Ap. J.*, **253**, 736.
Solinger, A., Morrison, P., and Markert, T. 1977, *Ap. J.*, **211**, 707.
Stocke, J. T., Liebert, J., Gioia, I. M., Griffiths, R. E., Maccacaro, T., Danziger, I. J., Kunth, D., and Lub, J. 1983, *Ap. J.*, **273**, 458.
Vader, J. P., van den Heuvel, E. P. J., Lewin, W. H. G., and Taken, R. J. 1982, *Astr. Ap.*, **113**, 328.
Vaiana, G. S., *et al.* 1981, *Ap. J.*, **245**, 163.
van Paradijs, J., and Verbunt, F. 1981, *Space Sci. Rev.*, **30**, 361.
van Speybroeck, L., Epstein, A., Forman, W., Giacconi, R., Jones, C., Liller, W., and Smarr, L. 1979, *Ap. J. (Letters)*, **234**, L45.
Visvanathan, N. 1974, *Ap. J.*, **192**, 319.
Visvanathan, N., and Sandage, A. R. 1972, *Ap. J.*, **176**, 57.
Watson, M. G., Willingale, R., Grindlay, J. E., and Hertz, P. 1981, *Ap. J.*, **250**, 142.
Watson, M. G., Willingale, R., Grindlay, J. E., and Seward, F. D. 1983, *Ap. J.*, **273**, 688.
Williams, T. B., Caldwell, N., and Schommer, R. A. 1984, *Ap. J.*, **281**, 579.
York, D. G. 1982, *Ann. Rev. Astr. Ap.*, **20**, 221.

R. E. Griffiths: Space Telescope Science Institute, Homewood Campus, Baltimore, MD 21218

V. Stanger and M. G. Watson: X-Ray Astronomy Group, Physics Department, University of Leicester, Leicester LE1 7RH, England, UK