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CORRELATED RADIO AND OPTICAL VARIABILITY IN THE BL LACERTAE OBJECT 0716+714

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ABSTRACT

We present results from simultaneous optical and radio observations of the BL Lacertae object 0716+714. During a 4 week period of continuous monitoring the source displayed in both wavelength regimes a transition between states of fast and slow variability with a change of the typical variability time scale from ~1 day to ~7 days. We interpret the simultaneous transition as evidence for intrinsic source variability, and we discuss some consequences for the optical and radio emission regions.

Subject headings: BL Lacertae objects — galaxies: jets — galaxies: nuclei — quasars — radio sources: variable

1. INTRODUCTION

Observations of optical and radio variability can provide important constraints for models of quasars and BL Lacertae objects. Statistically significant correlations between light curves in the two wavelength regimes have been found for several sources (e.g., BL Lacertae itself, Belov, Gagen-Torn, & Marchenko 1989; the quasar 3C 345, Bregman et al. 1986). Typically, the radio variability maxima lag behind those of the optical emission by ~1 to 2 yr, in agreement with the expectation that the optical flares should develop into radio outbursts on such time scales. In the quasar 3C 273, a correlation was found between ultraviolet (1250 Å) and radio (22 GHz), with a time lag of only 0.1 to 0.2 yr (Courvoisier et al. 1990). An even more direct link between the optical and radio emission regions is suggested by the observation of a swing in the polarization angle of OJ 287, which occurred almost synchronously at 10 GHz and in the optical (Kikuchi et al. 1988).

The above correlations are mainly based on long-term monitoring data, and so far little is known about blazar variability on time scales of hours to a few days. Optical variations have been observed on time scales as short as ~20 minutes (e.g., Moore et al. 1982; Miller, Carini, & Goodrich 1989). At centimeter wavelengths, a number of compact extragalactic sources vary with time scales of order 1 day with amplitudes up to ~25% (Witzel et al. 1986; Heeschen et al. 1987; Quirrenbach et al. 1989a).

Evidence for an intrinsic origin of rapid blazar variability comes from the observation that in the quasar 0917+624 quasi-periodic flux density variations are accompanied by variability of the polarized flux density (Quirrenbach et al. 1989b). Also, simultaneous radio and optical observations by Wagner et al. (1990) show that in three out of six sources rapid variations occurred in both wavelength regimes, whereas the remaining three objects were "quiet" in both spectral ranges.

To further investigate short time scale variability, we monitored for ~4 weeks in 1990 February a number of flat spectrum radio sources. Simultaneous radio and optical light curves were obtained with regular sampling at intervals of ~2 hr in the radio and a mean sampling of ~30 minutes during night time in the optical. In this *Letter*, we report the results for the BL Lacertae object 0716+714 at 6 cm and 6500 Å wavelength.

2. OBSERVATIONS AND DATA REDUCTION

The radio observations were carried out in 1990 February, with a four-antenna subarray of the National Radio Astronomy Observatory's Very Large Array (VLA).[7] 0716+714 was observed in two 50 MHz bands (centered at 4835 and 4885 MHz) for 5 minutes every 2 hr, giving a regular sampling except for occasional gaps due to electronics maintenance, etc.

Due to the ongoing antenna relocation from the D- to the A-array configuration, the four available antennas changed a few times. Since 0716+714 exhibits significant extended structure on the arcsecond scale (e.g., Antonucci et al. 1986), we chose antennas in such a manner that nearly identical points of the UV-plane were sampled each day. In addition, we used a 6 cm "snapshot" image of 0716+714 obtained in 1989 May with the VLA in B configuration to remove any effects of the extended structure from the calibrated visibilities. After averaging the visibilities of the six baselines, corrections (typically $\lesssim 2\%$) were applied for elevation dependent gain effects and changing weather conditions. From interleaved observations of the steep-spectrum (i.e., nonvariable) source 1311+678, we estimate the resulting rms accuracy of our flux density measurements to be ~0.8%; this is consistent with the result of similar observations in 1989 May (Witzel & Quirrenbach 1991).

The optical observations were carried out simultaneously with the 2.2 m telescope on Calar Alto, Spain, and the 0.71 m telescope of the Landessternwarte in Heidelberg, Germany. Both telescopes were equipped with Johnson *R* filters and CCD cameras. Aperture photometry was simulated on the

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same CCD frames for 0716+714 and several nonvariable comparison stars. A large number of exposures and good seeing conditions allowed the derivation of noise-free flat fields. The accuracy of the relative photometry was 0.8% to 1.2%, as determined from the rms scatter of the reference star measurements. Most nights had clear weather at least at one site; thus a nearly complete 12 hr night time coverage was achieved. The sampling rate varied between a few minutes and 2 hr, with a mean value of 2.2 measurements per hour. The observations at the two telescopes were consistent with each other within the observational accuracy. Details of the observational procedures will be given elsewhere.

3. RESULTS

Figure 1 shows light curves of 0716+714 at 6500 Å and at 6 cm. In the optical, these measurements range over of a factor of ~3 in brightness; in the radio, the overall peak-to-peak amplitude of the variations is ~25%. However, the data show a nearly simultaneous transition in brightness level accompanied by a change in variability time scale in both wavebands: during the beginning ("part 1") of our observations (before JD 2,447,930) the source varied with a typical time scale of ~1 day; around JD 2,447,930, a transition to a somewhat lower flux level occurred. Subsequently (after JD 2,447,930, "part 2"), the typical time scale of the variations is ~7 days in both wavelength regimes.

The change in variability time scale is also apparent in structure functions which we derived from the light curves (Fig. 2). Minima in these functions indicate the existence of a discrete time scale in the light curve. In the structure functions for part 1 (before JD 2,447,930; Figs. 2*a* and 2*b*), the first pronounced minima occur at ~1 day. Minima at ~7 days lag are apparent in the structure functions of the data taken after JD 2,447,930 (part 2). Other time scales at lags larger than those given above are due to the semiregular appearance of the light curves during the finite observing time.

Analysis of autocorrelation functions and power spectra gave results consistent with the structure functions. The general behavior is also seen in data which were obtained at 3.5 cm and in the Johnson *B* and *I* bands, although with poorer signal-to-noise or sampling.

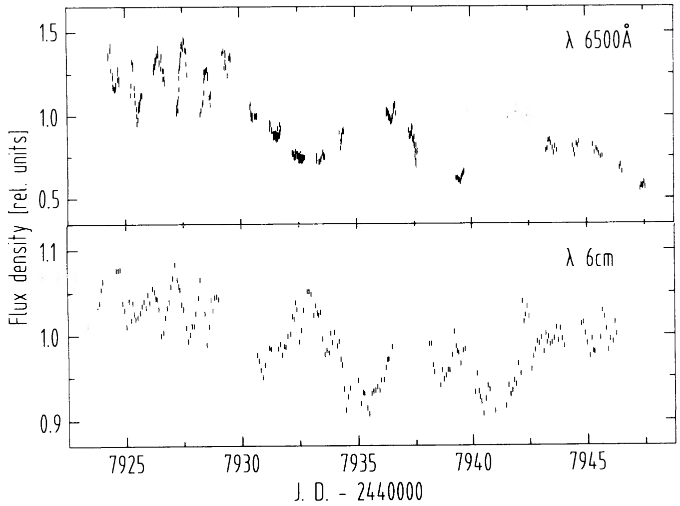

FIG. 1.—Optical (*top*) and radio (*bottom*) light curves of the BL Lacertae object 0716+714 (linear scales). In both light curves the mean flux density was set to 1, and fractional deviations from the mean are plotted on the *y*-axis.

The transition from a "fast" to a "slow" mode of variability provides a very strong argument for a real physical correlation between the optical and radio variability with a time lag not longer than a few days. In contrast to apparent correlations derived from a formal cross-correlation analysis of light curves with stationary statistical properties, near-simultaneous changes of the "mode" of the variability cannot easily be mimicked by a chance coincidence of physically uncorrelated peaks in the light curves.

In order to measure a possible time lag between radio and optical variability, we calculated the radio/optical cross-correlation functions separately for the two parts of the time series, using the discrete method described by Edelson & Krolik (1988). A correlation with a time lag of up to a few days is suggested by the cross-correlation function as well as direct inspection of the time series. However, due to the regular appearance of the light curves, the time lag cannot be determined without ambiguities.

4. DISCUSSION

It has not yet been unambiguously determined whether intraday radio variations are intrinsic to the sources or caused by propagation effects. The correlation between radio and optical variations in 0716+714 reported here implies that, at least in this source, the radio variations cannot be explained by refractive scintillation in the interstellar medium (RISS), and thus an intrinsic explanation is more likely. We note, however, that even at a wavelength of 6 cm compact sources are noticeably affected by RISS; this effect may give a minor additional contribution to the light curve of 0716+714 (Witzel & Quirrenbach 1991).

Gravitational microlensing has been ruled out as primary cause of the variability in the case of 0917+624, by the multifrequency signature in the radio data (Quirrenbach 1991), and by the short variability time scales (Wagner et al. 1991). For this source, even though RISS cannot be ruled out by the available radio data alone, an intrinsic origin of the variability again appears to be more likely: the polarization variability of 0917+624 can be accounted for much more easily in models based on shocks propagating in the milliarcsec scale jet (Qian et al. 1991).

The most puzzling consequence of rapid radio variations are the enormous apparent brightness temperatures implied by the light travel time argument. From radio variability, $T_B \gtrsim 10^{19}$ K is derived for 0917+624 ($z = 1.43$, H. Kühr 1989, private communication). No redshift is known for 0716+714, but the source is unresolved in deep images and therefore probably $z \geq 0.2$ (M. Stickel 1989, private communication). This results in a similar lower limit to T_B. To reconcile these values with the inverse Compton limit of 10^{12} K in the "standard" model, bulk relativistic motion with Lorentz factor $\gamma \gtrsim 100$ would be required. Although such high values of γ are not impossible a priori, this explanation is not fully satisfactory: virtually all other observational evidence is compatible with more moderate Lorentz factors, typically $\gamma \lesssim 10$.

There are several possibilities to explain very high brightness temperatures that do not take recourse to excessively high Doppler boosting. First, it is important to note that the standard correction factor $D^{-(3-\alpha)}$ (D is the Doppler factor, $S_\nu \propto \nu^\alpha$) for the brightness temperature is valid only for spherical symmetry of the emitting region in its rest frame. If the

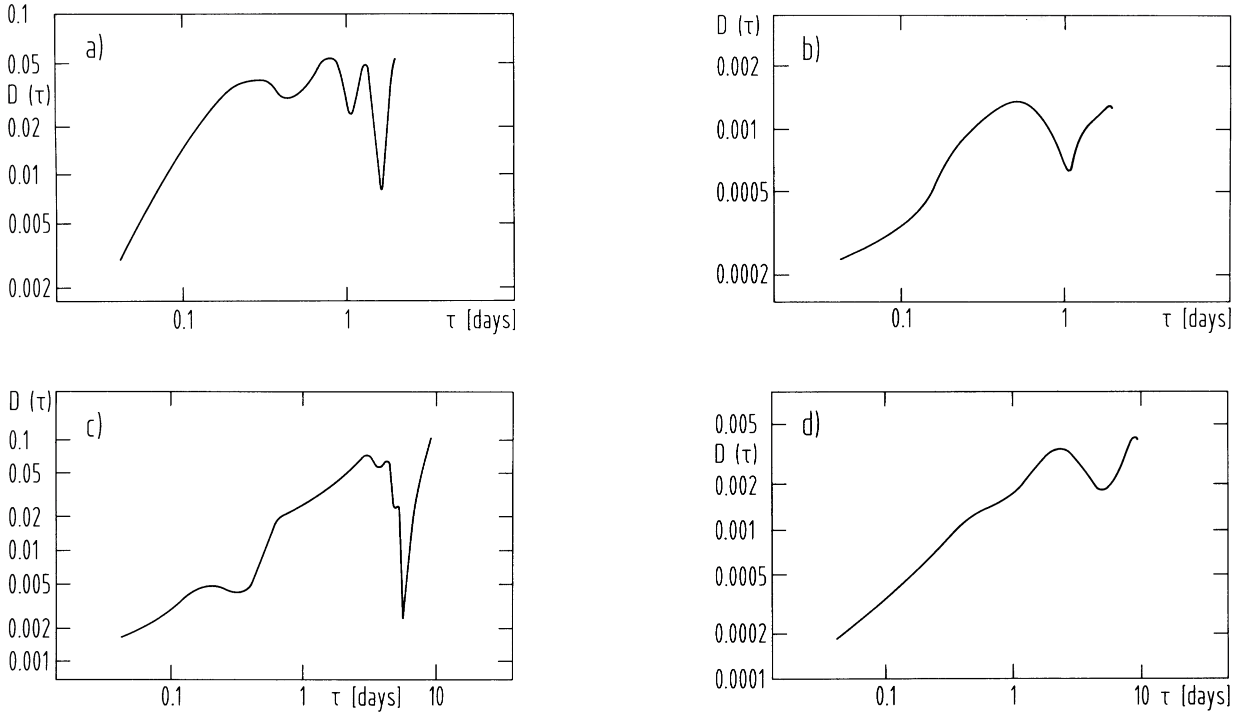

FIG. 2.—Structure functions $D(\tau) = \langle [S(t) - S(t + \tau)]^2 \rangle$ derived from the light curves in Fig. 1. The first part of the light curves corresponding to JD $\leq$ 2,447,930 is shown in Figs. 2*a* (optical) and 2*b* (radio), the second part corresponding to JD $\geq$ 2,447,930 is shown in Figs. 2*c* (optical) and 2*d* (radio).

observed variability is due to the interaction of a shock with irregularities in the electron density or magnetic field of the jet, the variability time scale is given by a longitudinal scale in the jet, whereas the brightness temperature is related to a transverse scale (for small angles to the line of sight). If in the rest frame of the flow the characteristic scale length in longitudinal direction is smaller than the jet radius, rapid variations could occur even for moderate intrinsic brightness temperatures. This means that preexisting structures are illuminated by the moving shock almost simultaneously, so that causality does not apply. In this picture, the ratio of the longitudinal scale to the jet radius must be taken into account; if the longitudinal scale is of the same order of magnitude as the jet radius in the rest frame of the source, this gives an additional factor γ^{-2} in the transformation of the brightness temperature. Then $\gamma \sim 10$ is sufficient for reconciling the apparent brightness temperature with the inverse Compton limit (Qian et al. 1991).

Secondly, the inverse Compton argument is based on assumptions which might be violated by some compact radio sources, at least episodically. For instance, brightness temperatures in excess of 10^{12} K can be generated by a population of relativistic electrons with anisotropic pitch angle distribution in an ordered field (Jones, O'Dell, & Stein 1974). Acceleration by electric fields may easily cause highly ordered electron beams. The time scale for isotropization may then be much longer than the synchrotron lifetime under the conditions met in the nuclei of active galaxies (Achatz, Lesch, & Schlickeiser 1990). Therefore, the electrons loose their energy mainly by incoherent synchrotron radiation, provided the energy density in the background photon field is not too large. The superposition of an anisotropic electron population generated locally in a small volume and a "standard" blazar nucleus could explain the observed variability without significantly changing our general picture of BL Lacertae objects.

Thirdly, coherent emission mechanisms are also capable of producing high brightness temperatures, but the coherence bandwidth of $\Delta\lambda/\lambda \sim 10^5$ required to produce the observed correlations makes such processes very unlikely.

We point out that the above hypotheses can be tested through imaging with extremely high resolution, as can be obtained by, e.g., space VLBI observations: the low T_B models based on geometric arguments predict an angular size of the source much larger than the one derived with the light travel time argument. In contrast, the model based on an anisotropic pitch angle distribution, or the assumption of bulk relativistic motion with $\gamma \sim 100$ imply smaller source sizes. In this case, variations due to RISS might play an additional important role, since the expected amplitude of scattering effects scales inversely proportional to the angular size of the source component.

It has been argued that the optical variability might be used to estimate an upper limit on the mass of the black hole postulated at the center of active nuclei. However, if one of the mechanisms discussed causes the correlated variability, the variable emission probably originates in a region in the jet which is small, yet at a considerable distance from the central engine. A black hole mass derived from the optical variations would then be questionable.

We conclude noting that the close correlation of radio and optical variability, together with the short time lag, demonstrates an intimate relationship between the corresponding emission regions. This places stringent constraints on the physical conditions in these regions and on the possible mechanisms of particle acceleration. Indeed it may call for a revision of some concepts generally used in the interpretation of variability data.

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REFERENCES

Achatz, U., Lesch, H., & Schlickeiser, R. 1990, A&A, 233, 391

Antonucci, R. R. J., Hickson, P., Olszewski, E. W., & Miller, J. S. 1986, AJ, 92, 1

Belov, V. N., Gagen-Torn, V. A., & Marchenko, S. G. 1989, Astrofizika, 30, 7 (English transl., Astrophysics, 30, 1)

Bregman, J. N., et al. 1986, ApJ, 301, 708

Courvoisier, T. J.-L., et al. 1990, A&A, 234, 73

Edelson, R. A., & Krolik, J. H. 1988, ApJ, 333, 646

Heeschen, D. S., Krichbaum, T., Schalinski, C. J., & Witzel, A. 1987, AJ, 94, 1493

Jones, T. W., O'Dell, S. L., & Stein, W. A. 1974, ApJ, 192, 261

Kikuchi, S., Inoue, M., Mikami, Y., Tabara, H., & Kato, T. 1988, A&A, 190, L8

Miller, H. R., Carini, M. T., & Goodrich, B. D. 1989, Nature, 337, 627

Moore, R. L., et al. 1982, ApJ, 260, 415

Qian, S. J., Quirrenbach, A., Witzel, A., Krichbaum, T. P., Hummel, C. A., & Zensus, A. 1991, A&A, 241, 15

Quirrenbach, A. 1991, in Variability of Active Galactic Nuclei, ed. H. R. Miller & P. J. Wiita (Cambridge: Cambridge Univ. Press), in press

Quirrenbach, A., Witzel, A., Krichbaum, T., Hummel, C. A., Alberdi, A., & Schalinski, C. 1989a, Nature, 337, 442

Quirrenbach, A., Witzel, A., Qian, S. J., Krichbaum, T., Hummel, C. A., & Alberdi, A. 1989b, A&A, 226, L1

Wagner, S. J., Sanchez-Pons, F., Anton, K., Quirrenbach, A., & Witzel, A. 1991, in Variability of Active Galactic Nuclei, ed. H. R. Miller & P. J. Wiita (Cambridge: Cambridge Univ. Press), in press

Wagner, S., Sanchez-Pons, F., Quirrenbach, A., & Witzel, A. 1990, A&A, 235, L1

Witzel, A., Heeschen, D. S., Schalinski, C., & Krichbaum, Th. 1986, Mitt. Astr. Ges., 65, 239

Witzel, A., & Quirrenbach, A. 1991, in Propagation Effects in Space VLBI, ed. N. Kardashev & L. Gurvits (Moscow), in press

1991ApJ...372L..71Q

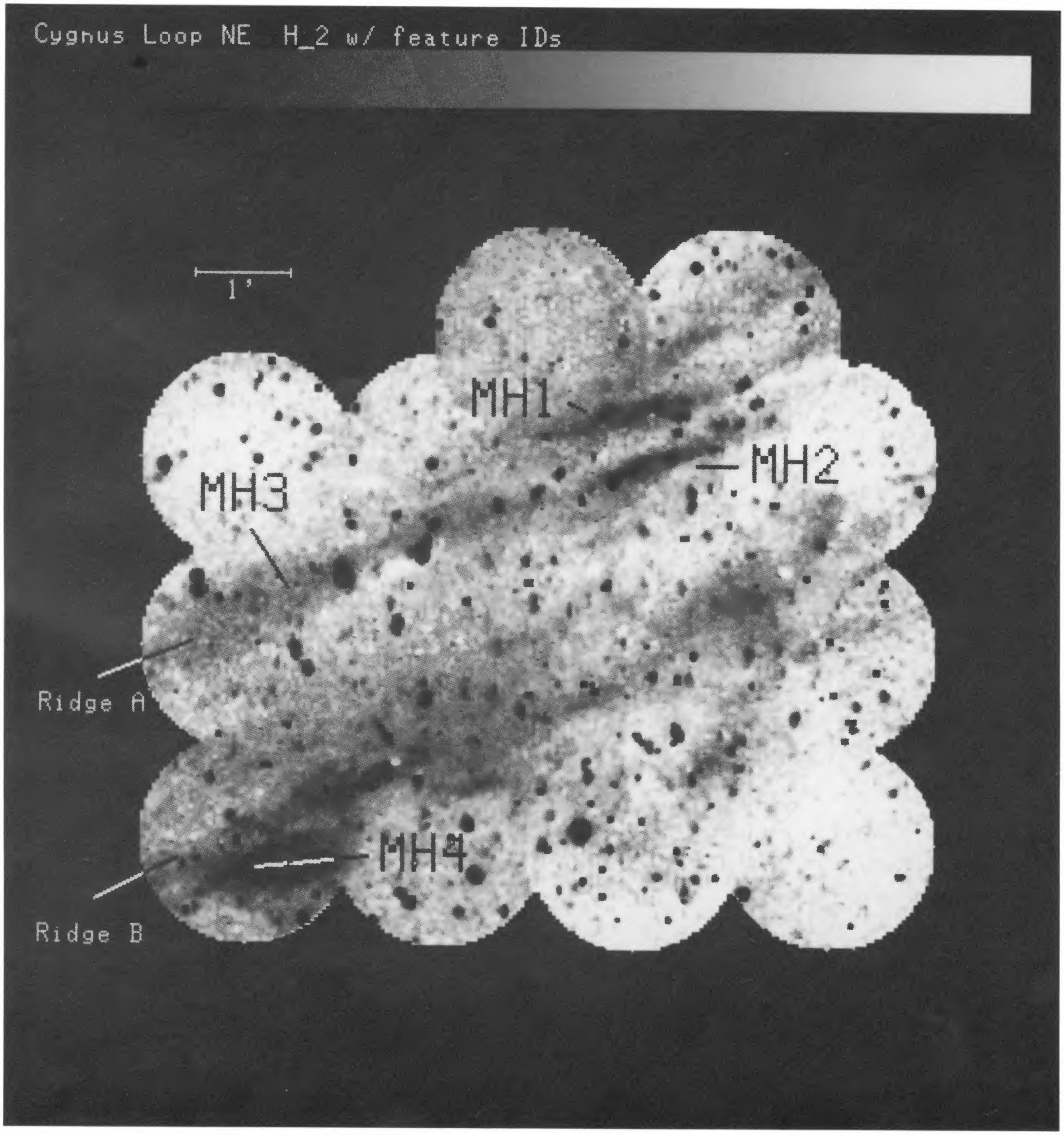

FIG. 1.—H_2 1–0 $S(1)$ mosaic of the NE part of the Cygnus Loop supernova remnant which shows the observed positions. Reproduced with permission from the Astronomical Journal (Graham et al. 1991). The image is not continuum subtracted, and many stars appear in the field. H_2 emission is associated with the bright optical emission in this region, but it is generally displaced in front of the edge of the optical line emission.

GRAHAM, WRIGHT, & GEBALLE (see 372, L21)