ULTRAVIOLET SIGNPOSTS OF RESONANT DYNAMICS IN THE STARBURST-RINGED Sab GALAXY M94 (NGC 4736)

WILLIAM H. WALLER,1,2 MICHAEL N. FANELLI,2,3 WILLIAM C. KEE1,4 RALPH BOHLIN,5 NICHOLAS R. COLLINS,2 BARRY F. MADORE,6 PAMELA M. MARCUM,7 SUSAN G. NEFF,8 ROBERT W. O'CONNELL,9 JOEL D. OFFENBERG,2 MORTON S. ROBERTS,10 ANDREW M. SMITH,8 AND THEODORE P. STECHER8

Received 2000 May 11; accepted 2000 October 31

ABSTRACT

The dynamic orchestration of star-birth activity in the starburst-ringed galaxy M94 (NGC 4736) is investigated using images from the Ultraviolet Imaging Telescope (UIT; far-ultraviolet [FUV] band), Hubble Space Telescope (HST; near-ultraviolet [NUV] band), Kitt Peak 0.9 m telescope (Hα, R, and I bands), and Palomar 5 m telescope (B band), along with spectra from the International Ultraviolet Explorer (IUE) and the Lick 1 m telescope. The wide-field UIT image shows FUV emission from (1) an elongated nucleus, (2) a diffuse inner disk, where Hα is observed in absorption, (3) a bright inner ring of H ii regions at the perimeter of the inner disk (R = 48″ = 1.1 kpc), and (4) two 500 pc size knots of hot stars exterior to the ring on diametrically opposite sides of the nucleus (R = 130″ = 2.9 kpc). The HST Faint Object Camera image resolves the NUV emission from the nuclear region into a bright core and a faint 20″ long “minibar” at a position angle of 30°. Optical and IUE spectroscopy of the nucleus and diffuse inner disk indicates a ∼107–108 yr old stellar population from low-level star-birth activity blended with some LINER activity. Analysis of the Hα-, FUV-, NUV-, B-, R-, and I-band emissions, along with other observed tracers of stars and gas in M94, indicates that most of the star formation is being orchestrated via ring-bar dynamics, involving the nuclear minibar, inner ring, oval disk, and outer ring. The inner starburst ring and bisymmetric knots at intermediate radius, in particular, argue for bar-mediated resonances as the primary drivers of evolution in M94 at the present epoch. Similar processes may be governing the evolution of the “core-dominated” galaxies that have been observed at high redshift. The gravitationally lensed “Pretzel Galaxy” (0024+1654) at a redshift of z ∼ 1.5 provides an important precedent in this regard.

Key words: galaxies: evolution — galaxies: individual (M94, NGC 4736) — galaxies: kinematics and dynamics — galaxies: photometry — galaxies: spiral — ultraviolet emission

1. INTRODUCTION

Star-forming rings or “pseudorings” are common to early- and intermediate-type spiral galaxies (see Athanassoula & Bosma 1985; Buta, Purcell, & Crocker 1995; Buta & Combes 1996), including our own Milky Way (see Gusten & Mezger 1982; Clemens, Sanders, & Scoville 1988; Waller 1990a). Such ringlike accumulations of gas and associated star-birth activity may have helped to build the inner parts of many primeval disk galaxies (Friedli & Benz 1995), as exemplified by the recent discovery of a starburst-

1 Department of Physics and Astronomy, Tufts University, Medford, MA 02155.
2 Raytheon ITSS Corporation, Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center, Code 681, Greenbelt, MD 20771.
3 Department of Physics, University of North Texas, Denton, TX 76203.
4 Department of Physics and Astronomy, University of Alabama, P.O. Box 570324, Tuscaloosa, AL 35487-0324.
5 Space Telescope Science Institute, Homewood Campus, Baltimore, MD 21218.
6 Infrared Processing and Analysis Center, California Institute of Technology, M/S 100-22, 770 South Wilson Avenue, Pasadena, CA 91125.
7 Department of Physics, Texas Christian University, Box 298840, Fort Worth, TX 76129.
8 Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center, Code 680, Greenbelt, MD 20771.
9 Department of Astronomy, University of Virginia, P.O. Box 3818, Charlottesville, VA 22903.
10 National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903-2475.

ringed galaxy at z ∼ 1.5 (Colley, Tyson, & Turner 1996; Tyson, Kochanski, & Dell'Antonio 1997). The formation and maintenance of these starburst rings are often attributed to orbital resonances with rotating bar or “oval” asymmetries in the stellar disks (see Combes 1994; Byrd et al. 1994; Combes et al. 1995; Buta & Combes 1996; and references therein). However, other dynamical mechanisms—including gravitational instabilities (Elmegreen 1992, 1994; Kenney & Jogee 1997), outward propagating star formation (Walker, Lebofsky, & Rieke 1988; Waller, Gurwell, & Tamura 1992), and even radially driven pileups from nuclear outbursts (Waller et al. 1992; Tenorio-Tagle et al. 1997)—may play significant roles in orchestrating some of the starburst rings that are observed.

As the closest early-type spiral galaxy of low inclination, M94 (NGC 4736) has received concentrated attention from both observers and theorists. This RS(A)r+ab—type galaxy (de Vaucouleurs et al. 1991) is noted for its inner ring of ongoing starburst activity (R ∼ 45″), oval stellar distribution at intermediate radius (R ∼ 220″); see Mulder & van Driel 1993; Mulder 1995; Mollenhoff, Matthias, & Gerhard 1995), and outer stellar ring near its de Vaucouleurs radius

11 Collisionally induced “ring galaxies,” such as the Cartwheel Galaxy, are thought to be morphologically and dynamically distinct from the more common ringed galaxies considered herein (see Athanassoula & Bosma 1985; Marcum, Appleton, & Higdon 1992).
Figure 1 (extracted from the Digital Sky Survey using the SkyView utility; McGlynn, Scollick, & White 1998)\(^{12}\) shows the outermost portions of M94, highlighting the oval disk and outer pseudoring.

The inner starburst ring is a prominent source of H\(_2\), H\(_i\), and CO emission (Smith et al. 1991; Mulder & van Driel 1993; Gerin, Casoli, & Combes 1991). The discovery of compact thermal and nonthermal radio sources in the ring (Duric & Dittmar 1988) indicates the presence of dense H\(_{\text{II}}\) regions and young supernovae remnants. The ring’s velocity field can be described by a combination of circular rotation with velocities of order 200 km s\(^{-1}\) and residual noncircular motions of order 15 km s\(^{-1}\) (Mulder 1995) to 25 km s\(^{-1}\) (Buta 1988), depending on the adopted inclination and major-axis position angle.

Interior to the ring, the bright bulge and inner disk show twisted isophotes at red and near-IR (NIR) wavelengths, indicative of a weak barlike distortion (Beckman et al. 1991; Shaw et al. 1993; Mollenhoff et al. 1995). Far-IR (FIR) and CO observations interior to the ring reveal a rich interstellar medium (ISM), with gas surface densities exceeding that of the ring (Smith & Harvey 1994; Garman & Young 1986; Gerin et al. 1991; Wong & Blitz 2000).

Optical spectroscopy of the nuclear region yields LINER-type emission lines, along with absorption lines from the circumnuclear stellar population, consistent with an early main-sequence stellar turnoff (A4–A7) and corresponding age of \(~500\) Myr (Pritchett 1977; Keel 1983; Taniguchi et al. 1996). Further support for a young central population comes from NIR spectroscopy, which shows deep CO absorption bands from red giant and asymptotic giant branch stars of similar age (Walker et al. 1988). These authors have proposed an outward propagating mode of star formation, whereby NGC 253, M82, M94, and M31 represent increasingly evolved versions of the same starbursting sequence. Although the kinematics of the ring show very little evidence for outward expanding motions (contrary to prior claims of bulk expansion; van der Kruit 1974, 1976), they also do not preclude a scenario for radially propagating star formation. Other investigators have modeled the inner and outer rings in terms of resonant dynamics mediated by bar or “oval” potentials interior to the rings (Gerin et al. 1991; Shaw et al. 1993; Mollenhoff et al. 1995; Mulder & Combes 1996), with the observed noncircular motions resulting from dispersion orbits near the Lindblad resonances (Buta 1988).

In this paper, we present and discuss new observational clues to the dynamical mechanisms governing the star formation in M94. The ultraviolet images obtained by the Ultraviolet Imaging Telescope (UIT), in particular, reveal

---

\(^{12}\) NASA’s SkyView facility (http://skyview.gsfc.nasa.gov) was developed and is maintained under NASA ADP grant NAS 5-32068 at NASA’s Goddard Space Flight Center.
hitherto unrecognized patterns of recent star formation, whose presence lends further support to the hypothesis of galaxy evolution via bar-mediated resonances. The various imaging and spectroscopic observations and reductions are described in § 2. The resulting far-ultraviolet (FUV), near-ultraviolet (NUV), Hx-, R-, and I-band emission morphologies are presented and compared in § 3. Radial intensity profiles and other photometric comparisons are discussed in § 4. UV and optical spectroscopy of the inner disk and nucleus is presented in § 5. Kinematic properties and inferred dynamical scenarios are considered in § 6. Our summary of the wavelength-dependent morphological, photometric, and dynamical properties of M94 appears in § 7, wherein evolutionary implications are discussed.

In the following sections, we assume a distance to M94 of 4.6 \((75/H_0)\) Mpc, based on the galaxy’s recession velocity of 345 km s\(^{-1}\) with respect to the Local Group (Sandage & Tammann 1981). The corresponding spatial scale is 22.3 pc arcsec\(^{-1}\). Unresolved sources imaged by Hubble Space Telescope’s (HST) Faint Object Camera (FOC)

2. OBSERVATIONS AND REDUCTIONS

A log of the ultraviolet and visible imaging is presented in Table 1. A listing of complementary UV and visible spectra is shown in Table 2.

2.1. Ultraviolet Imaging

The UIT imaged M94 in the FUV \((\lambda_0 = 1521 \text{ Å}, \Delta \lambda = 354 \text{ Å})\) on 1995 March 12 as part of the 16 day Spacelab/Astro-2 mission aboard the space shuttle Endeavour. This wide-field telescope images 40′ fields of view at ∼3″ resolution. In the case of M94, the UIT image represents the only extant UV image of the entire galaxy (see Fig. 2a). The 1040 s exposure was obtained with a dual-stage image intensifier with CsI photocathodes and was recorded on carbon-backed H160 Kodak film. After processing the film and scanning the emulsion, the resulting digitized “density image” was fog-subtracted, flat-fielded, linearized to “exposure units,” and calibrated to flux units using International Ultraviolet Explorer’s (IUE) observations of standard stars (see Stecher et al. 1992, 1997; Waller et al. 1995 and references therein). Correction for image distortion produced by the magnetically focused image intensifiers was carried out according to the procedures described by Greason et al. (1994). The resulting corrections amounted to a few arcseconds in the field center (which includes all of M94’s FUV emission) increasing to 10″–20″ near the edge of the 40′ field of view. Astrometry was tied to 10 compact knots evident in both the FUV and B-band images (see the next subsection). Positions in the resulting distortion-corrected image are good to ∼3″, and the spatial resolution is of similar magnitude.

The HST’s FOC imaged the center of M94 in the NUV \((\lambda_0 = 2300 \text{ Å}, \Delta \lambda = 500 \text{ Å})\) on 1993 July 18—before the optical repair mission—as part of a UV-imaging survey of 110 large nearby galaxies (Maoz et al. 1995, 1996). After standard STScI pipeline processing, the 596 s NUV exposure has a 22″ × 22″ field of view at 0″022 pixel\(^{-1}\) (see Fig. 2a). The spherical aberration of HST’s primary mirror resulted in a point-spread function (PSF) featuring a sharp core with a FWHM ≈ 0″05 and about 15% of the total light surrounded by an extensive halo of several arcseconds radius containing most of the energy. Following Maoz et al. (1996), our calibration of the detected FOC counts into flux densities assumes a conversion of \(1.66 \times 10^{-17} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1} \text{ count s}^{-1}\), while noting that the PHOTFLAM conversion in the image header is \(2.017 \times 10^{-17} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1} \text{ count s}^{-1}\). Flux uncertainties are estimated at ∼5% over large areas, increasing to ∼20% for compact sources (Maoz et al. 1995, 1996 and references therein).

2.2. Visible Imaging

A wide-field \((9''66 \times 9''66)\) B-band image was obtained with the Palomar 5 m telescope and Tek3 CCD camera (1024 × 1024 pixels) on 1994 February 11 under hazy skies. This 600 s exposure is saturated in the central 2′, but contains high signal-to-noise (S/N) detections of the oval disk and parts of the outer ring. Astrometry of this image is tied to the positions of several foreground stars, as measured on

---

TABLE 1

Log of Images (as Presented)

| Telescope | Camera/Filter   | Image Number | R.A. (J2000.0) | Decl. (J2000.0) | t(exp) (s) | Date         |
|-----------|-----------------|--------------|----------------|---------------|-----------|--------------|
| UIT 0.38 m| FUV/B1 band     | 2508         | 12 50 52.88    | 41 07 19.52   | 1040      | 1995 Mar 12 |
| HST 2.4 m | FOC/F152W       | x1ar5401t    | 12 50 53.04    | 41 07 12.68   | 596       | 1993 Jul 18 |
| Hale 5 m  | TEK3/B band     | ...          | 12 50 52.19    | 41 07 10.39   | 600       | 1994 Feb 11 |
| KPNO 0.9 m| RCA-1/R band    | ...          | 12 50 52.88    | 41 07 19.52   | 60        | 1986 Feb 18 |
|            | RCA-1/I band    | ...          | 12 50 52.88    | 41 07 19.52   | 100       | 1986 Feb 18 |
|            | RCA-1/Hz band   | ...          | 12 50 52.88    | 41 07 19.52   | 1055      | 1986 Feb 18 |
| Oschin 1.23 m | Schmidt/J band | ...          | 12 50 53.04    | 41 07 13.80   | ...       | ca. 1957     |

Note—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
a corresponding image in the Digitized Sky Survey (STScI 1994).\textsuperscript{14}

Ground-based Hα-, R-, and I-band images of M94 were obtained with the now retired KPNO 0.9 m telescope and RCA-1 CCD camera (508 × 316 pixels) on 1986 February 17.\textsuperscript{15} These images have 7.28 × 4.53 fields of view at 0.86 pixel\textsuperscript{-1}. Sky conditions varied from photonically hazy, yielding PSFs of about 2′ (FWHM). Astrometry is tied to five foreground stars that are common to the KPNO (Hα, R, and I band) and Palomar (B-band) images. For calibration purposes, spectrophotometric standard stars (BD 26 2606 and HD 84937) were imaged before and after the target imaging. Subtraction of the red continuum from the Hα-band image was carried out with the R-band image according to the formulations in Waller (1990b), whereby corrections were made for the ~38% [N II] \( \lambda \lambda 6548, 6584 \) contribution to the total Hα + [N II] line emission and resulting ~15% contamination of the Hα image after transmission by the 36 Å bandwidth Hα filter. A pure red continuum image was also produced by removing the contaminating Hα + [N II] line emission from the R-band image (Waller 1990b; see Fig. 2a).

Photometry of the Hα emission from the 7.3 × 4.5 field yields a total flux of \( 9.9 \times 10^{-12} \) ergs cm\(^{-2}\) s\(^{-1}\), 14% higher than that determined by Kennicutt & Kent (1983) within a 7′ diameter aperture (after correcting for a 38% [N II] contamination within their 100 Å bandwidth). The starburst ring (\( R = 30′ \rightarrow 60′ \)) is measured to have \( f(\text{Hα}) = 9.6 \times 10^{-12} \) ergs cm\(^{-2}\) s\(^{-1}\), which is nearly 1.8 times higher than that obtained by Smith et al. (1991) from the 75 Å bandwidth image of Pogge (1989). Some of these discrepancies can be attributed to the varying bandpasses and corresponding uncertainties in the [N II] emission being transmitted, vagaries in the continuum subtraction, problematic Hα absorption produced by A-type stars in the inner disk (see §4.2), and final calibration (Smith et al. 1991).

Because of hazy conditions during the I-band exposure, calibration of the I-band image was done by bootstrapping to the I-band radial intensity profiles resulting from the photoelectric photometry of Muñoz-Tuñón et al. (1989) and the \( R-I \) color profiles of Beckman et al. (1991).

\textbf{2.3. \textit{UV Spectroscopy}}

FUV (1200–2000 Å) and NUV (2000–3200 Å) spectra of M94’s inner disk were obtained from the \textit{IUE} archive. The \textit{IUE} data were accessed via the \textit{IUE} Data Analysis Center at NASA/GSFC\textsuperscript{16} and are representative of the New Spectral Image Processing System.

Table 2 lists the image numbers, dates, exposure times, nominal positions, and roll angles of the low-resolution FUV (SWP) and NUV (LWP and LWR) \textit{IUE} spectra. Here, SWP, LWP, and LWR, respectively, refer to \textit{IUE}’s short-wavelength prime, long-wavelength prime, and long-wavelength redundant cameras. Figure 3 shows the \textit{IUE} apertures (20′ × 10′) on gray-scale images of the FUV emission, where the mapping is based on the nominal positions and roll angles of the FUV (SWP) and NUV (LWP & LWR) observations. Although the accuracy of the nominal positions is of order ±10″, Figure 3 indicates that the apertures were most likely sampling the inner disk rather than the starburst ring. Table 2 notes which apertures are filled with disk (‘d’) and/or nuclear (‘n’) emission, based on visual inspection of the overlays. The limiting spectral resolution of these data is about 6 Å.

\textbf{2.4. \textit{Visible Spectroscopy}}

Ground-based visible spectra (3800–7500 Å) were obtained from the Lick 1 m Nickel Telescope and Image Dissecting Spectrograph (IDS). The summed spectrum of the central region (8′1 circular aperture) is a mean flux average of 64 minutes in blue and red grating settings, with

\begin{table}[h]
\centering
\caption{Log of \textit{IUE} Spectra}
\begin{tabular}{lllllll}
\hline
\textbf{Number} & \textbf{Camera/No.} & \textbf{R.A. (J2000.0)} & \textbf{Decl. (J2000.0)} & \textbf{P.A. (deg)} & \textbf{t(exp) (s)} & \textbf{Date (day/year)} & \textbf{Notes} \\
\hline
1 & SWP 15887 & 12 50 52.71 & 41 07 15.20 & 185 & 13500 & 361/1981 & dn \\
2 & SWP 15905 & 12 50 52.71 & 41 07 15.20 & 183 & 18000 & 364/1981 & dn \\
3 & SWP 28042 & 12 50 51.28 & 41 07 08.22 & 81 & 10200 & 87/1986 & d \\
4 & SWP 28043 & 12 50 53.01 & 41 07 10.24 & 81 & 4200 & 87/1986 & nd \\
5 & SWP 28047 & 12 50 54.79 & 41 07 14.27 & 80 & 11400 & 88/1986 & d \\
6 & SWP 28380 & 12 50 53.80 & 41 07 30.22 & 26 & 15240 & 86/1986 & d \\
7 & SWP 54247 & 12 50 53.50 & 41 07 08.22 & 81 & 14700 & 95/1995 & nd \\
\hline
\end{tabular}
\end{table}
Fig. 2.—(a) UV and R-band imaging of M94. The field of view is 7.28 × 4.53. North is up, and east is to the left. The UIT’s FUV image shows the starburst ring in high contrast against a mostly dark disk. Exterior to the ring are two hitherto unrecognized 500 pc size bisymmetric knots on diametrically opposite sides of the nucleus. The HST’s NUV image (see inset) shows a 450 pc long nuclear minibar that had been previously inferred from photometric analyses of optical-band images. By comparison, the R-band image shows the underlying bulge and oval disk made up of cooler and typically older stars. (b) Radial distribution of FUV intensities (surface brightnesses) reveals strong enhancements at the nucleus and starburst ring, along with regularly spaced low-level enhancements, which are associated with arcs of FUV emission interior to the ring.
Fig. 3.—Location of *IUE* apertures with respect to the inner disk and nucleus of M94. Numbers refer to the entries in Table 2. Positional accuracy is estimated at $\pm 10''$. (a) Overlay of *IUE*’s FUV (SWP) apertures on the UIT/FUV image of M94, showing both nuclear and disk-dominated observations. (b) Overlay of the *IUE*’s NUV (LWP and LWR) apertures on the UIT/FUV image of M94.
16 minutes in an intermediate setting to ensure the overlap area is well calibrated. The spectrum has been rebinned to 2.5 Å pixels from the original, which still oversamples the resolution of ≤ 10 Å FWHM. We note that adjacent pixels in the IDS spectrum are not statistically independent, yielding detections similar to those of a noncentroiding photon counter, which spreads single photons across several output pixels.

We complement this composite spectrum with analysis of the image-dissector scanner data presented by Keel (1983) and discuss a new high-resolution spectrum, obtained with the 2.5 m Isaac Newton Telescope (INT) on La Palma, using the Intermediate Dispersion Spectrograph with an image photon counting system (IPCS) detector.\(^\text{17}\) The 1" slit was oriented approximately along the major axis (P.A. = 135°) for this 1000 s exposure. There is a useful signal over 45 spatial increments of 0.6 e each. We consider equivalent widths of the lines, along with spectral slopes and discontinuities of the continuum emission.

3. ULTRAVIOLET AND VISIBLE MORPHOLOGIES

Figure 2a shows the dramatically different morphologies that are detected at ultraviolet and visible wavelengths. The inner disk and bulge component, which is so prominent at \(R\) band, completely disappears in the FUV image. The oval disk at intermediate radius also has no FUV counterpart. Instead, the FUV image is characterized by (1) an extended and elongated nucleus, (2) a diffuse inner disk, (3) a bright inner ring at the perimeter of the inner disk (\(R = 48'' = 1.1\) kpc), and (4) two 500 pc size knots exterior to the ring (\(R = 130'' = 2.9\) kpc).

3.1. Nuclear Region

The insert in Figure 2a contains the \(HST/FOC\) pre-COSTAR image of the nuclear region (Maoz et al. 1995, 1996). This NUV image shows a marginally resolved nucleus (FWHM ≈ 0.1') embedded in a bright core of ≈ 1" (22 pc) diameter, along with a faint "minibar" that has a total length of 20" (450 pc) at a P.A. of approximately 30°. Low-level ripples in the emission (which are included in the estimate of the bar's total length) are evident at 2", 5", and 9" to the southwest of the nucleus. Maoz et al. (1995) attribute these features to bow shocks or tidal arms, resulting from a recent merger event. However, we see that the ripples overlap with the larger concentric arcs, which are evident in the UIT/FUV image at projected radii of ≈ 9" and 15" (see the next subsection). Similar ripples are also present in an archival \(HST/WFPC2\) \(V\)-band image of this region with connections to larger spiral arcs. To the north of the nucleus are two point sources, whose flux densities are consistent with those of single B-type supergiant stars (see § 4).

3.2. Inner Disk

The UIT/FUV emission from the inner disk includes concentric FUV arcs to the southwest of the nucleus that can be traced for ≈ π radians (≈ 700 pc). These arcs are of low contrast and, because of the noise characteristics of the UIT imaging, are not amenable to typical contrast-enhancement techniques (e.g., median filtering). However, they do show up as enhancements in the radial distribution of intensities (see Fig. 2b). Typical spacing between the arcs is 9° (200 pc), with additional features at 15° and 34°. The arcs themselves appear to show some substructure at the limits of resolution.

Contrary to a merging scenario (Maoz et al. 1995), which would seem to be precluded by the lack of significant tidal effects beyond the inner few hundred parsecs, these features more likely indicate an orbital dynamic at work in the inner disk. At an interpolated orbital velocity of 140 km \(s^{-1}\) and corresponding shear rate of \(-1360\) km \(s^{-1}\) kpc\(^{-2}\) (see § 6), such features could have been differentially swept out over a timescale of ≈ 20–100 Myr. This estimated timespan is consistent with a population of late B-type stars, whose main-sequence lifetimes are of a similar duration.

The UIT/FUV image of the inner disk also shows a brighter arc to the north, just inside the starburst ring at a radius of 40' (see Fig. 2b), along with widespread diffuse emission at a level amounting to \(≈ 15\%\) of the mean surface brightness of the ring. The nature of these resolved and unresolved FUV components is uncertain, although some clues can be obtained from the longer wavelength imagery.

At \(H\alpha\), the inner disk appears in absorption with respect to the continuum emission from the underlying population of stars. The strongest absorbers at \(H\alpha\) are the photospheric atmospheres of B- and A-type stars, whose temperatures are sufficiently cool for hydrogen to remain neutral and sufficiently warm for a significant population of the H Balmer (\(n = 2\)) electronic energy level (see Mihalas 1978). In the UIT/FUV image, the diffuse light from the inner disk probably arises from these same stars. Indeed, the UIT/FUV image represents the first view of this young stellar population, unconfused by the longer wavelength emission from the older inner disk and bulge components.

Figure 4 compares a spatially filtered \(R\)-band image with an \(R-I\) color image of the inner disk. The spatially filtered \(R\)-band image (Fig. 4a) was created by median smoothing the \(R\)-band image over a 13" × 13" window and then subtracting the smoothed image from the original. The resulting fine-scale structure includes the nuclear minibar previously noted by Mollenhoff et al. (1995) and Mulder (1995), along with a "dark" spiral arc of diminished emissivity to the west and other flocculent spiral structures associated with the starburst ring. The archival \(HST/WFPC2\) \(V\)-band image of this region resolves the flocculent structure into spiral dust lanes of high-pitch angle that cross through the nearly circular ring.

The \(R-I\) color image (Fig. 4b) shows reddening along the western spiral arc seen in (Fig. 4a) and in another arc to the northeast, along with blue knots in the starburst ring. None of the fine-scale structures and reddened features in the optical inner disk have counterparts in the UIT/FUV image. Therefore, neither emitting nor absorbing structures nor reddening dust lanes in the old disk can be defining the observed concentric FUV arcs to the southwest and northeast. We infer that the FUV arcs are recently generated structures of emitting B- and A-type stars and/or scattering clouds of low-dust optical depth. We further speculate that the emitting and/or scattering FUV sources, being relatively young, are distributed in a much thinner disk than that associated with the optical fine-scale structures and reddened features, thus explaining the morphological differences between these two wavelength regimes. Further insights on the stellar content of the inner disk can be gained from the \(IUE\) spectroscopy presented in § 6.

---

\(^{17}\) The Isaac Newton Telescope is operated by the Royal Greenwich Observatory on behalf of the SERC at the Spanish Observatorio del Roque de los Muchachos.
Fig. 4. (a) Nuclear minibar and inner disk: Spatial filtering of the R-band image (shown in Fig. 2) shows a minibar with the same approximate extent and P.A. as that seen in the HST’s NUV image. Optical and UV spectroscopy of this region indicate a stellar population with an early main-sequence turnoff (A4–A7) superposed on an older G-type population belonging to the central disk and bulge. The inner disk shows dark spiral arcs of relatively lower surface brightness that connect with the starburst ring. (b) Color morphology: The $R - I$ color image is coded so that dark features denote relatively red colors, and bright features denote bluer colors. The image shows reddened arcs to the west and northeast, along with especially blue knots in the starburst ring.
Fig. 5a

Fig. 5b

Fig. 5.—(a) Inner disk in the light of Hα. After scaling and subtracting the underlying red continuum emission, the residual Hα line emission shows concentrations in the starburst ring and in (only) one of the bisymmetric FUV knots. The nucleus and innermost disk show a net deficit due to Hα absorption by the atmospheres of the B- and A-type stars that dominate the light in these regions. (b) Ratio of Hα and FUV emission in the inner disk: No radial displacement in the Hα/FUV intensity ratio is evident across the starburst ring, contrary to outward- or inward-propagating star-birth scenarios.
3.3. Starburst Ring

The inner starburst ring in M94 is the single dominant emission feature in the FUV, Hα, and radio continuum bands. Rectification of the galaxy to its nominal face-on orientation (P.A. = 120°, i = 40°; Mulder & van Driel 1993) shows that the ring is almost perfectly circular, with a mean radius of 47'' (1.1 kpc) and a FWHM of 21'' (0.49 kpc). The latter measurement is based on doubling the measured half-width at half-maximum of the emission beyond the mean radius, thereby excluding the diffuse contribution interior to the ring. Adopting an inclination of 35°, as in the dispersion orbit model of Buta (1988), would yield a finite but small ellipticity of 0.063, with a 16° offset between the kinematic line of nodes and projected major axis. We are not able to further constrain the ring’s orientation and so shall continue to assume an inclination of 40°, based on the H I study of Mulder & van Driel (1993).

A comparison of the FUV and Hα morphologies reveals strong similarities. Figure 5a shows the Hα emission, and Figure 5b shows the ratio of Hα and FUV intensities in the inner disk and ring. Except for the spiral-like ridges of enhanced Hα emission to the west-northwest and east-southeast, very little coherent variation in this ratio is evident in the ring. In particular, the intensity ratios do not
show any radial displacement in the FUV emission relative to that at Hα. From this lack of radial structuring in the Hα/FUV ratio, we can conclude that little evidence is found for outward- or inward-propagating starburst activity, as explained below.

A morphological comparison of Hα- and FUV-emitting regions provides a useful means of tracking sequential patterns of star formation in disk galaxies. The Hα emission is dominated by the most massive and short-lived stars ($M \geq 20 M_\odot$), while the FUV emission arises mostly from less massive, longer-lived stars ($20 \leq M/M_\odot \leq 2.5$). For an evolving star cluster with an initial mass function (IMF) typical of local star-forming regions, the Hα emission typically reaches a maximum within a million years of the star-forming episode and quickly decays with an e-folding timescale of about 3 Myr. By contrast, the FUV emission reaches a maximum at about 3 Myr (due to the onset of B-type supergiants), decaying to 1/e in yet another 3 Myr. The Hα/FUV ratio is seen to decrease by 2 orders of magnitude after 10 Myr (e.g., Hill et al. 1995). Subsequently, the Hα emission will vanish, while the FUV declines slowly for the next few 100 Myr.

In the outward propagating starburst scenario, the Hα emission would concentrate where the propagating wave front is located—on the outer perimeter of the FUV-emitting ring. Inward propagating scenarios would have the Hα emission interior to the FUV ring. Spatial displacements of Hα and FUV emission have been observed across the spiral arms of M51 (O’Connell 1997; Petit et al. 1996), M74 (Marcum et al. 1997), and NGC 4258 (Courtès et al. 1993). These displacements have been interpreted as the result of spiral density waves concentrating gas along the
insides of the spiral arms and the subsequent migration of the evolving clusters past the spiral wave fronts. Given the resolution of our images (~100 pc) and characteristic timescale between Hα and FUV maxima (3 Myr), any residual propagation of starburst activity would have to proceed at a speed less than 35 km s⁻¹ to avoid detection. Implications of this propagation speed limit are discussed in §7.

The armlike enhancements in the Hα/FUV ratio correspond to similar features in a recent CO mapping with the BIMA interferometer (Wong & Blitz 2000). These armlike extensions away from the ring have further analogues at B band, where a complex spiral pattern is evident (see the next subsection).

3.4. Bisymmetric Knots and Associated Spiral Structure

One of the most remarkable aspects of M94's FUV emission morphology is the pair of knots on diametrically opposite sides of the nucleus. Both knots have projected radii of approximately 130′ (2.9 kpc). A line drawn through the knots intersects the nucleus at a P.A. of 105°, intermediate between the P.A.'s of the inner starburst ring (127°) and the oval disk (95°) (Mollenhoff et al. 1995). The two knots are roughly 20′ (500 pc) in size, with the eastern knot showing the more complex structure. Only the eastern knot shows significantly in our continuum-subtracted Hα image (Fig. 5). Other much smaller knots of FUV emission appear at low S/N to the southwest, south-southwest, east-northeast, and north-northeast. The southwest, south-southwest, and east-northeast knots have faint counterparts in the light of Hα, while all of these features have counterparts at B band (see below).

Figures 6a and 6b, respectively, show the B-band image before and after spatial filtering. The filtering in this case involves median smoothing over a 30′ × 30′ window and then dividing the original image by this smoothed image. Such median-normalized spatial filtering reveals a fine-scale structure over a wide range of surface brightnesses (e.g., Waller et al. 1998). Here, it highlights the starburst ring and bisymmetric knots as significant enhancements above the disk at B band. The filtered image also reveals many flocculent spiral arms outside of the ring, whose relation with the knots is somewhat ambiguous. The western knot appears part of a dominant arm with a "shingled" morphology connecting to the ring in the northeast. The eastern knot appears to be associated with several arms, including one that would be the symmetric counterpart to the arm that links the western knot to the ring. The marginally detected FUV knots to the southwest, south-southwest, east-northeast, and north-northeast all show enhanced B-band emission from associations of massive stars among the myriad spiral arms.

In summary, the bisymmetric FUV knots have B-band counterparts that appear to be part of the complex spiral arm structure at these radii. Their symmetric prominence on opposite sides of the nucleus, however, requires a dynamical explanation that is spatially more specific than that of the arms. Similarly, the starburst ring can be regarded as an especially bright, tightly wound component of the overall spiral pattern, whose prominence also indicates special dynamical circumstances.

Bisymmetric knots or plumes have been noted in other ringed-barred galaxies, including NGC 1433 (Buta 1986), NGC 7020 (Buta 1990), NGC 7098 (Buta 1995), and IC 4214 (Buta & Combes 1996). As discussed in these papers, the symmetric features are likely tracing dynamical resonances that are connected with the general ring-bar phenomenon.

4. PHOTOMETRIC RESULTS

4.1. Nuclear Photometry

From the UIT and HST/FOC images, circular-aperture photometry of the nucleus out to a radius of 5′ yields m(FUV) = 14.7 mag and m(NUV) = 13.5 mag, respectively. The resulting FUV−NUV color of 1.2 mag is significantly redder than that derived from IUE spectra of the inner disk (see the next section). Between 5′−10′ radii, the nonnuclear emission is significantly bluer than that derived using IUE, with FUV−NUV ≈ −0.3. The latter colors indicate the presence of late-B and hotter stars, depending on the amount of reddening (Fanelli et al. 1992). Estimates of the reddening have been derived from the visible colors (Smith et al. 1991; see also the next subsection), visible spectra, and subsequent modeling of the stellar populations (Taniguchi et al. 1996; Pritchett 1977). The resulting estimates of visual extinction are 0.5–1.0 mag in the nuclear region, corresponding to UV color excesses of E(FUV−NUV) = 0.1–0.2 mag. Therefore, the corrected (FUV−NUV)₀ color of the nucleus could be close to 1.0 mag or the equivalent of a stellar population with a late A-type stellar cutoff (Fanelli et al. 1992).

The nonnuclear point sources in the HST/FOC/NUV image of the nuclear region provide helpful checks on the distance to M94. For the brightest point source, Mãoz et al. (1996) lists a monochromatic flux of f₁(2300 Å) = 2.6 × 10⁻¹⁶ ergs s⁻¹ cm⁻² Å⁻¹ [m₁(2300 Å) = 17.9 mag]. This source is unresolved at a resolution of 0′1 and corresponding linear scale of <2.2 pc at the assumed distance. Although an extremely compact star cluster cannot be ruled out, this exceptional UV source is most likely dominated by a single hot supergiant star. In the absence of extinction, a B0-2 Ia-O supergiant star has M(NUV) ≈ −10.7 mag (Fanelli et al. 1992), which would imply a distance modulus of m − M = 28.6 mag and corresponding distance of 5.2 Mpc. Assuming nuclear color excesses of E(B−V) = 0.15–0.27 mag (Taniguchi et al. 1996) and Galactic-type extinction law, the corresponding NUV extinctions would be A(NUV) ≈ 1–2 mag, and the revised distances would be 3.3–2.1 Mpc, respectively. The adopted distance of 4.6 Mpc can thus be regarded as a reasonable estimate, given the uncertainties in stellar spectral type and extinction. The second source, 1′ to the east, is 6 times (1.9 mag) fainter, consistent with it being an A0-2 Ia-O supergiant at this distance, if subject to the same amount of extinction. Were the galaxy significantly closer, more abundant OBA-type giant and main-sequence stars would be resolved, which is not the case.

4.2. Surface Photometry of the Disk

Figure 7 shows radial profiles of the FUV surface brightness and cumulative flux. These profiles were derived from annular-averaged photometry, using elliptical annuli consistent with the adopted P.A. (120°) and inclination (40°). Since Galactic extinction is negligible toward M94 (de Vaucouleurs et al. 1991), no correction was made. The resulting surface brightness profile (Fig. 7) is dominated by light from the nucleus, inner disk, starburst ring, and an exponentially declining disk that is punctuated by an enhancement from the bisymmetric knots at R = 130′. The exponentially...
declining component between 50° and 80° radii has an e-folding scalelength of only 10" (223 pc), similar to that found at the R and I bands (see Muñoz-Tuñón et al. 1989). The FUV emission beyond the bisymmetric knots also shows a steep decline with an estimated scalelength of 20" (446 pc), significantly shorter than the 70" scale length measured at the R and I bands in the outer disk (Muñoz-Tuñón et al. 1989).

The cumulative flux profile (Fig. 7) indicates that the half-light radius matches that of the starburst ring and that more than 80% of the total FUV emission is contained within a radius of 60" (1.3 kpc). The total FUV flux from M94 is $f_{\lambda}(1520 \, \text{Å}) = 6.02 \times 10^{-13} \, \text{ergs cm}^{-2} \, \text{s}^{-1} \, \text{Å}^{-1}$, corresponding to $F(\text{FUV}) = 9.45 \, \text{mag}$ or $M(\text{FUV}) = -18.91 \, \text{mag}$ at the adopted distance of 4.6 Mpc.

The corresponding FUV luminosity of $1.5 \times 10^{49} \, \text{ergs s}^{-1} \, \text{Å}^{-1}$ is the photometric equivalent of $2 \times 10^4$ Orion nebulae (Bohlin et al. 1982) or about 90 30 Doradus regions (as measured on an UIT/FUV image of 30 Dor out to a radius of 5' [67 pc]), before correcting for the extinction in these sources. Adopting a Salpeter IMF with lower and upper mass limits of 0.1 and 100 $M_\odot$, respectively, yields an uncorrected star formation rate (SFR) of 0.15 $M_\odot \, \text{yr}^{-1}$. This SFR estimate assumes continuous star formation and includes the strong contribution of B supergiant stars to the overall luminosity. An overall visual extinction of 1 mag would increase the global luminosity and inferred SFR by about a factor of 11 (Hill et al. 1997). At this rate, it would have taken ~10 Gyr to transform the dynamical mass of $1.6 \times 10^{10} \, M_\odot$ that is present within 60" of the nucleus (Garman & Young 1986) into the dominant stellar component that we see today.

As a check on these star-birth estimates, we note that the measured Hα flux of $9.6 \times 10^{-12} \, \text{ergs cm}^{-2} \, \text{s}^{-1}$ converts to a luminosity of $L(\text{Hα}) = 2.45 \times 10^{40} \, \text{ergs s}^{-1}$, or only 5600 equivalent Orion nebulae. The origin of this discrepancy is deferred to the next subsection. Assuming case B recombination and multiplying the Hα luminosity by $7.4 \times 10^{11}$ yields a photoionization rate of $n_e = 1.8 \times 10^{52} \, \text{photons s}^{-1}$ and a corresponding SFR of 0.22 $M_\odot \, \text{yr}^{-1}$. The similarity of the FUV- and Hα-based SFRs, before correcting for extinction, suggests either that insignificant obscuration is present in the photometrically dominant starburst ring or that significant obscuration exists with other mechanisms making up for the greater attenuation of the FUV emission relative to the longer wavelength Hα emission. Such mechanisms include (1) an excess contribution of nonionizing B-type stars to the total FUV emission, (2) a reduction of the total Hα emission due to Hα absorption by the atmospheres of B- and A-type stars, and (3) the absorption of EUV photons before they ionize the gas and induce Hα emission. Likely EUV absorbers include the nebular dust associated with the H II regions, as well as the various metal species in the O-type stellar atmospheres themselves (see Hill et al. 1997; Waller, Parker, & Malumuth 1996). We conclude in the next subsection that modest obscuration plus nonionizing contributions to the total FUV emission best explain the observed levels of Hα and FUV emission. Stellar absorption at Hα is probably less than a 10% effect overall, given Hα emission equivalent widths of order 100 Å in the ring, and stellar absorption equivalent widths peaking at less than 10 Å.

The global (total) FUV $- V$ color of M94 is 1.21 mag, which is characteristic of early-type disk galaxies with circumnuclear starburst activity (e.g., NGC 1068, NGC 3351; Waller et al. 1997). The $R - I$ colors shown in Figure 4b do not vary as much as those found by Beckman et al. (1991) in their photometric study. Bootstrapping our measured intensity ratio in the nuclear region to a color of $R - I = 0.45 \, \text{mag}$ as reported by Beckman et al. (1991), we obtain colors that range from $R - I = 0.3 \, \text{mag}$ in the ring’s starburst knots to $R - I = 0.5 \, \text{mag}$ in the arcs interior to the ring. Beckman et al. (1991) obtain much bluer colors of order 0.1 mag near the ring. We attribute this discrepancy to our having used the Hα-band image to remove contaminating line emission from the R-band image (Waller 1990b), thereby reducing the red flux from the knots in the ring by 20%. Comparison of the contaminated and uncontaminated R-band images confirm our attribution.

If the reddened arcs are caused by dust, the corresponding color excess relative to that of the starburst knots would amount to $E(B - V) \approx E(R - I) = 0.2 \, \text{mag}$ or the equivalent visual extinction of roughly 0.6 mag in excess of the knots. Allowing for bluer stellar populations in the knots could reduce the estimate of excess extinction in the arcs to negligible levels, while inclusion of some internal reddening in the knots would increase the total estimated extinction by $\lesssim 1 \, \text{mag}$. Such low estimates for the extinction are similar to the spectroscopic results obtained by Pritchett (1977) and by Taniguchi et al. (1996) in their studies of the nuclear region, where color excesses of 0.27 and 0.15 mag, corresponding to $A_V = 0.86$ and 0.48 mag, were, respectively, obtained.

### 4.3. Photometry of the Starburst Ring and Knots

Photometry of the FUV and Hα emission from the starburst ring (between projected radii of 30" and 60") yields a mean Hα/FUV flux ratio (in equivalent width units) of 22 Å. By way of comparison, we note that this flux ratio is somewhat lower than that found in the Orion Nebula (38 Å; Bohlin et al. 1982), within the range of flux ratios evident in M33’s giant H II regions (GHRs; 19–69 Å; Parker, Waller, & Malumuth 1996) and close to the mean of M51’s wide-ranging GHRs (29 ± 23 Å; Hill et al. 1997).

A model of steady state star formation with a Salpeter-type IMF yields a somewhat lower ratio of 16 Å, while a modeled 2 Myr old starburst would match our result (Hill et al. 1995 [see their Fig. 10]). Such a short burst timescale is probably untenable, thus indicating some need to correct our FUV flux for extinction. For 1 mag of visual extinction, the resulting “corrected” Hα/FUV flux ratio would be
lower by a factor of ~5, leading to a modeled burst age of 6 Myr—close to the age limit of the ionizing O stars. Based on these considerations alone, we surmise that the FUV and Hα emission from the starburst ring is subject to no more than 1 mag of visual extinction (on average). We also can conclude that the similarity in uncorrected SFRs based on the global FUV and Hα fluxes is probably coincidental. After correction for 0.5–1.0 mag of visual extinction, the Hα flux would be increased by a factor of 1.4–2.1, while the FUV emission would increase by a factor of 3.3–11. In other words, the FUV emission is tracing an additional nonionizing Population I component in the inner disk that is missed at Hα and, after correction for extinction, is contributing to the overall calculated rate of star formation.

The bisymmetric FUV knots to the west and east of the ring have fluxes of $3.0 \times 10^{-15}$ and $3.8 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ Å$^{-1}$, respectively. This translates to the equivalent of 100 and 127 Orion nebulae, respectively. Only the eastern knot shows significant Hα emission, with a flux of $2.57 \times 10^{-13}$ ergs cm$^{-2}$ s$^{-1}$ and, hence, an Hα/FUV flux ratio of 67 Å—about twice that of the Orion Nebula—thus indicating greater FUV obscuration than is present in Orion or a hotter ionizing cluster. Examination of the spatially filtered B-band image (Fig. 6b) reveals dark spiral arm features at the position of the eastern knot that may correspond to obscuring dust clouds. The western knot shows similar structures to one side. The lack of significant Hα emission from this knot is difficult to explain with dust, and is most likely due to the presence of an older ($\tau > 10$ Myr), nonionizing stellar population.

5. SPECTROSCOPIC RESULTS

5.1. FUV Spectroscopy

Figure 8a shows an average of 5 IUE/SWP spectra of the extranuclear emission from the inner disk. Based on the aperture mapping shown in Figure 3a, some emission from the nucleus may be present but at low levels. The wavelengths of commonly observed FUV absorption and emission lines are indicated on the spectrum for comparison. Although the averaged spectrum is of generally low S/N, several features can be identified. Of these, the most prominent are the absorption blends of S II (1250–1259) and Si II (1260, 1265), the P-Cygni profile of S IV (1394,1443), the absorption blends of Fe III (1601–1611), Al III (1600–1612), C II (1720–1722), and Al II (1719–1725), and part of the broad absorption complex of Fe III (1891–1988). The low-ionization lines, in particular, are most characteristic of B- and A-type stars. The strength of the blueshifted S IV absorption feature relative to that of C IV (1550), along with the strong Si II absorptions at 1260,1265 and 1527,1533 Å, indicate a composite spectral type later than B3 but earlier than B8 (Fanelli et al. 1992; Kinney et al. 1993; Walborn, Parker, & Nichols 1995). The absorptions at 1470, 1780, and 1790 Å remain unidentified.

In emission, there is some evidence for C IV ($\lambda\lambda1548$–1551), He II ($\lambda1640$), N m $\lambda\lambda1730$, $\lambda1750$, and C m $\lambda\lambda1909$—much of which may be the result of the LINER activity being scattered by the ISM in the inner disk. The C m $\lambda\lambda1909$ emission may be responsible for filling in part of the broad stellar absorption complex of Fe III ($\lambda\lambda1891$–1988).

5.2. NUV Spectroscopy

Figure 8b shows an average of two IUE/LWP spectra of the disk. The most prominent spectral features are the absorption lines of Fe II ($\lambda\lambda2609, 2750$), Mg II ($\lambda2800$), and Mg I ($\lambda2852$). Comparison with stellar spectra from the IUE Spectral Atlas (Wu, Crenshaw, & Blackwell 1991) shows that Mg II ($\lambda2800$) is unusually weak relative to Mg I ($\lambda2852$); the line ratios in this spectral range being consistent with light dominated by late G-type stars, based on this cursory comparison. However, the spectrum is too blue, and the amplitude of the 2800 Å break too small for this to be the whole story. Comparison with the nuclear
spectra (IUE LWR 12221, 12238 as listed in Table 2) shows evidence for a spectrally smooth blue component off the nucleus proper. Also, the Mg II 2800 Å break is roughly 50% smaller than that evident in the nuclear spectrum (see below).

All the absorption features are broader in the off-nuclear spectrum, because the light there almost uniformly fills the aperture (so centering shifts are not an issue). The off-nuclear spectrum shown here is not only bluer but shows a diminished 2800 Å break amplitude. Measured as a ratio of flux $F_a$ above and below 2800 Å, the ratio is 2.5 at nucleus and 1.8 away from it. Using the spectral-break indices developed by Fanelli et al. (1992), we obtain for the off-nucleus averaged spectrum (Mg II $\lambda$2800–Mg II $\lambda$2852) = 0.31 mag, ($\lambda$2609/$\lambda$2660) = 0.45 mag, and ($\lambda$2828/$\lambda$2921) = 0.31 mag—all of which are consistent with a $B-V$ color of 0.2–0.3 mag or the equivalent of a late A-type main-sequence star or late A- to early F-type giant/ supergiant star.

The off-nuclear continuum is likewise flatter in the SWP range, with little trace of the emission-like features around 1900 Å seen in the nuclear spectrum (see Kinney et al. 1993). These properties can be accounted for, if recent star formation (a few times $10^8$ years ago) contributes relatively more light off the nucleus than on it, consistent with an aging burst that is spatially more extended than the centrally concentrated stars of the older disk and bulge.

5.3. Optical Spectroscopy

Figure 8c shows the spectrum of optical emission from the central D = 8.1, as obtained with the Lick 1 m telescope and IDS. Absorption lines include the Ca II K and H and lines at 3934 and 3968 Å, H $\delta$ ($\lambda$4101), CH G band ($\lambda$4300), H $\gamma$ ($\lambda$4340), He II ($\lambda$4686), H $\beta$ ($\lambda$4860), Mg I ($\lambda$5170), Fe I ($\lambda$5270), Na D ($\lambda$5890, 5896), H $\alpha$ ($\lambda$6563), and atmospheric absorption bands of O$_2$ ($\lambda$6867) and H$_2$O ($\lambda$7186). Emission lines are restricted to [N II] ($\lambda$6584) and [S II] ($\lambda$6713).

The H $\beta$ equivalent width of about 5.4 Å is huge for an old population typical of spiral bulges, even before any correction for line emission. There has been star formation in this region not long ago. The 4000 Å break is also suppressed, indicating the effective age is much younger than for typical early-spiral bulges. Following the Dressler & Shectman (1987) definition (ratio of $F_*$ between 3950–4050 and 3750–3850 Å), the observed break has $F_*$ = 1.6, whereas values of 1.9–2.0 are more usual.

From the IDS/IPCS on the 2.5 m INT, we see that the nucleus (inner 1” or so) is bluer at optical wavelengths than its immediate surroundings. Misalignment in the IPCS detector is less than 0.1 pixel, so this is not an obvious instrumental effect. This nuclear blueing effect is substantial, amounting to about 30% over the 4400–5200 Å range (more or less equivalent to $\Delta B$) = −0.3 mag, where the mean $B-V$ color of the bulge is 0.91 mag, which is already bluer than ordinary Sa/Sb bulges; Keel & Weedman 1978). Outside this area, the color along the slit is quite constant out to 15” from the nucleus, where the signal begins to die out. This effect has no observed counterpart in the IUE spectra, because of their courser spatial resolution.

The prominent H $\beta$ absorption line in the nuclear INT/IPCS spectrum has FWHM 18–20 Å, consistent with values seen in mid- to late-A stars. Thus, the data are consistent with seeing the main-sequence turnover near this spectral type, rather than the supergiant dominance of a much younger population giving superficially similar spectral features (as seen in the starbursting nucleus of NGC 4569; Keel 1996).

The optical spectra confirm our imaging result that Hz is in absorption with respect to the continuum from the underlying population of A- and B-type stars. By contrast, the neighboring line of [N II] (6584 Å) is seen in emission in the Lick/IPCS spectrum. As previously noted, H $\beta$ is also dominated by photospheric absorption. The IDS/IPCS spectrum shows some H $\gamma$ emission, at least at the nucleus, that is not swallowed by the stellar absorption line.

6. KINEMATICS AND DYNAMICS

Figure 9a shows the rotation curve based on the H I observations of Mulder & van Driel (1993), where key morphological features are noted. This curve is qualitatively similar to that obtained from a recent interferometric mapping of CO (Wong & Blitz 2000) but is, on average, 12% lower owing to our adoption of a 40° inclination compared with their 35°. Figure 9b shows the corresponding radial profiles of H I and H $\gamma$ gas, the latter being derived from the CO observations of Gerin et al. (1991).

The molecular gas component clearly dominates the inner disk’s ISM and may continue to prevail at higher radii, where the CO emission has yet to be measured. The plotted extrapolation beyond the last reliable measurement of CO emission is intended to provide an upper limit on the total gas and thus a lower limit on the Q stability index (see below). The interferometric measurements by Wong & Blitz (2000) yield even lower extrapolated surface densities of gas, consistent with our extrapolated upper limit. Moreover, FIR measurements with IRAS and the KAO (Smith et al. 1991) reveal negligible dust emission beyond 60â€œ radius, further corroborating the gas upper limit used here. The H I profile, though of lower amplitude, shows enhancements at the radii of the starburst ring and the bisymmetric knots.

Figure 9c shows the corresponding radial profile of the gravitational stability index (Q). Here, we have considered the simplest case of the gaseous stability, without any coupling with the stellar component, such that

$$Q = \frac{\Sigma_{\text{crit}}}{\Sigma_{\text{gas}}} = \frac{\kappa \sigma}{\pi G \Sigma_{\text{gas}}} ,$$

where the epicyclic frequency $\kappa$ is closely linked to the rotation curve $\nu(R)$ through

$$\kappa^2 = \frac{2v}{R} \left( \frac{v}{R} + \frac{dv}{dR} \right) ,$$

and where $\sigma$ is the gas velocity dispersion—a quantity that is not well constrained but is probably of order 5–10 km s$^{-1}$. Here, we leave $\sigma$ as an unknown. The resulting radial profile of Q/σ out to the limits of the CO observations shows a shallow minimum at the radius of the starburst ring. Although this minimum is too broad and shallow to explain the more discrete and prominent starburst ring, it may help to explain the relatively young ($10^7$–$10^8$ yr) stellar population pervading the inner disk.

Figure 10 shows the orbital resonance diagram that results from the rotation curve along with the radii of key morphological features. A single wave pattern speed of 35 km s$^{-1}$ kpc$^{-1}$ (where $d = 4.6$ Mpc) would place the nuclear bar inside the inner inner Lindblad resonance (IILR), the starburst ring between the IILR and outer inner Lindblad resonance (OILR), the bisymmetric knots at the 4:1
“ultraharmonic” resonance (UHR), the oval disk terminating at corotation (CR), and the outer pseudoring at the outer Lindblad resonance (OLR). Alternatively, a higher pattern speed of 56 km s$^{-1}$ kpc$^{-1}$ (as modeled by Mulder & Combes 1996) would move the starburst ring just outside the OLR, the bisymmetric knots to the CR radius, and the edge of the oval disk to the OLR. This latter model, however, fails to account for the outer ring without invoking additional patterns.

Further support for the proposed sequence of resonances comes from specific ratios of the corresponding radii (see Buta 1986). Given a flat rotation curve, the modeled ratio of OLR and UHR radii is $r(\text{OLR})/r(\text{UHR}) = 2.6$. If these OLRs and UHRs are, respectively, traced by the outer pseudoring and bisymmetric knots, then we obtain a ratio of radii equaling 2.54, closely matching the modeled ratio. The theoretical ratio of OLR and CR radii, being $r(\text{OLR})/r(\text{CR}) = 1.7$, is also well matched by the observed relative dimensions of the outer ring and oval disk, where a ratio of 1.5 is obtained.

Admittedly, morphological tracers and rotation curves are insufficient to discriminate between these and other possible kinematic patterns (see Buta & Combes 1996). Further progress on constraining the resonant dynamics in M94 will require analysis of the complete velocity field in the disk (see Westpfahl & Adler 1996; Canzian & Allen 1997). A complete H I mapping with the VLA has been made recently, whose spectral and spatial resolution would be sufficient to derive a complete velocity field and its associated resonant states (D. Westpfahl, private communication). Until such an analysis is carried out, we think that the resonant state diagrammed in Figure 10 best explains the most features with the fewest conditions.

7. CONCLUSIONS AND IMPLICATIONS

Through UV-optical imaging and spectroscopy, we have found new evidence for bar-mediated resonances as the primary drivers of evolution in M94 at the present epoch.
Our observational results include evidence for the following:

1. A 450 pc long nuclear minobar at both optical and NUV wavelengths.
2. An inner disk with diffuse FUV emission in concentric arcs that do not match the fine-scale structures or reddened structures at visible wavelengths. Since Hz is observed in absorption here, the UIT/FUV image represents the first view of this nonionizing but relatively young disk component.
3. UV-optical colors and spectral indices in the nucleus and inner disk that indicate B- and A-type stars in the presence of modest extinction ($A_V \leq 1$ mag), along with some LINER activity from the nucleus itself.
4. A 2.2 kpc diameter starbursting ring at the perimeter of the inner disk, which is bright at FUV, Hα, and radio continuum wavelengths. The level of star-birth activity in this inner ring rivals the levels observed in starbursting irregular galaxies, such as NGC 1569 and 4449. The inferred SFR within the ring and inner disk amounts to 1.5 $M_\odot$ yr$^{-1}$—sufficient to build up the stellar mass of the inner disk and bulge in $\sim 10^{10}$ yr.
5. No detectable radial offsets between the Hz and FUV rings, thus indicating a 35 km s$^{-1}$ speed limit to any outward- or inward-propagating star formation in the ring, if such a mode is present.
6. Two 500 pc size FUV-emitting knots exterior to the ring on diametrically opposite sides of the nucleus. The bisymmetric knots and starburst ring appear to be especially prominent parts of a complex spiral arm structure, as revealed in a spatially filtered B-band image.
7. The starburst ring, bisymmetric knots, oval disk, and outer pseudoring as signposts of resonant dynamics in the disk of M94. More specifically, the radii of these features match those of various orbital resonances, given a pattern speed of 35 km s$^{-1}$ kpc$^{-1}$ at our adopted distance and inclination. These orbital resonances are most likely driven by some combination of the nuclear minobar and oval distortion in the disk.
8. A shallow minimum of gravitational stability at the radius of the starburst ring that extends inward into the inner disk. Although too broad to explain the discrete starburst ring, the shallow minimum may help to explain the $10^7$–$10^8$ yr old stellar population interior to the ring.

Although we can set a limit on the speed of outward- or inward-propagating star formation in the ring, we cannot preclude the existence of such a mode. At a propagation speed of 35 km s$^{-1}$, a wave initiated in the nucleus could traverse the inner disk to the radius of the current starburst ring in only 31 Myr. Therefore, it is possible that the $10^7$–$10^8$ yr old stellar population detected in the inner disk is the result of such an outward-propagating wave. The striking difference in emission morphologies at FUV and red wavelengths provides further support for the starburst ring being a transient phenomenon that does not persist at any one radius for very long. Either these resonant phenomena come and go, as the oval distortions undergo secular evolution, or their operating radii migrate in response to other dynamical influences on the stars and gas (see Combes 1994; Combes et al. 1995; Friedli & Benz 1995). Otherwise, one must invoke strong radial inflows of stars from the starburst ring to populate the inner disk and bulge, a feat requiring unusual circumstances, e.g., mergers.

The results reported herein may have important implications with regard to observations of the most distant observable galaxies. At redshifts of 1–5, the 2 kpc diameter starburst ring in M94 would subtend angles of only $(0.7'-1.0')H_0/75$ in an Einstein–de Sitter Universe ($q_0 = 5$) and $(0.3'-0.2')H_0/75$ in an open (Milne) universe ($q_0 = 0$; see Narlikar 1983). The UV-bright nuclear rings evident in NGC 1097, 1317, 1433, 1512, 2997, 4321, and 5248 (Maoz et al. 1995, 1996; Kuchinsky et al. 2001; Marcum et al. 2001) would subtend even smaller angles at the same redshifts. Moreover, nuclear rings tend to have higher FUV surface brightnesses than their larger counterparts—the inner ring in M94 being a remarkable exception. Therefore, some of the “core-halo” morphologies that are evident at high redshift in the rest-frame FUV (see Giavalisco et al. 1997) may in fact be marginally resolved representations of galaxies with starburst rings in their centers.

Gravitationally lensed galaxies are fortuitously magnified, enabling resolutions of their structure at high S/N. An important precedent in this regard is the gravitationally lensed Pretzel Galaxy, which lies behind the galaxy cluster 0024+1654 at an estimated redshift of 1.2–1.8 (Colley et al. 1996; Tyson et al. 1997). Detailed reconstructions of the multiply-lensed galaxy show a clear annular morphology on a scale of several kiloparsecs. If M94 and other nearby ringed galaxies can be used as current-epoch analogues, the Pretzel Galaxy and perhaps other marginally resolved core-halo galaxies at high redshift may represent youthful inner disks and bulges growing under the organizing influence of oval or bar asymmetries (Friedli & Benz 1995; Waller et al. 1997). Conversely, if evidence for starburst rings at high redshift proves to be sparse, then massive inner disks featuring ring-bar dynamics have yet to form in most systems, or starbursting bulges are masking their presence.

We thank David Adler, Gene Byrd, Francoise Combes, Daniel Friedli, and David Westpfahl for generously providing consultation on the dynamics of ringed-barred spiral galaxies. W. H. W. is grateful to John Huchra and the OIR division of the Harvard-Smithsonian Center for Astrophysics for their kind hospitality during his visiting appointment at the CfA. W. H. W. also thanks Eric Murphy and Christine Winslow, Tufts undergraduates who helped craft some of the graphics. UIT research is funded through the Spacelab Office at NASA headquarters under project number 440-51. We are deeply grateful to the crew of STS-67 and the many people who helped make the Astro-2 mission a success. W. H. W. acknowledges partial support from NASA’s Astrophysics Data Program (071-96adp).

REFERENCES

Athanassoula, E., & Bosma, A. 1985, ARA&A, 23, 147
Beckman, J. E., Varela, A. M., Muñoz-Tuñón, C., Völk, J. M., & Cepa, J. 1991, A&A, 245, 436
Bohlin, R. C., Hill, J. K., Stecher, T. P., & Witt, A. N. 1982, ApJ, 255, 87
Bosma, A., van der Hulst, J. M., & Sullivan, W. T., III. 1977, A&A, 57, 373
Buta, R. 1986, ApJS, 61, 631
———. 1988, ApJS, 66, 233
———. 1990, ApJ, 356, 87
———. 1995, ApJS, 96, 39
Buta, R., & Combes, F. 1996, Fundam. Cosmic Phys., 17, 95
