ABSTRACT

Before the official first-light images, the *Chandra* X-Ray Observatory obtained an X-ray image of the field to which its focal plane was first exposed. We describe this historic observation and report our study of the first *Chandra* field. *Chandra*’s Advanced CCD Imaging Spectrometer (ACIS) detected 15 X-ray sources, the brightest being dubbed Leon X-1 to honor the *Chandra* telescope scientist Leon Van Speybroeck. Based on our analysis of the X-ray data and spectroscopy at the European Southern Observatory (ESO; La Silla, Chile), we find that Leon X-1 is a type-1 (unobscured) active galactic nucleus (AGN) at redshift $z = 0.3207$. Leon X-1 exhibits strong Fe Kα emission and a broad-line Balmer decrement that is unusually flat for an AGN. Within the context of the eigenvector-1 correlation space, these properties suggest that Leon X-1 may be a massive ($\geq 10^8 M_\odot$) black hole, accreting at a rate approaching its Eddington limit.

*Subject headings:* galaxies: active — history and philosophy of astronomy — X-rays: general

1. INTRODUCTION

On 1999 July 23 00:31 EDT (1999:204:04:31 UTC), after attempts on the evenings of July 19 and July 21, the Space Shuttle *Columbia* mission STS-93 was launched from NASA’s Kennedy Space Center. A little over 7 hr later, *Columbia* deployed the *Chandra* X-Ray Observatory. (For a detailed description of the observatory and its instruments see, e.g., Weisskopf et al. [2003] and references therein.) About an hour thereafter, two firings of the attached solid-rocket Inertial Upper Stage and subsequent separation sent *Chandra* toward a high elliptical orbit. Five burns of *Chandra*’s Integral Propulsion System, on July 24, 25, and 27 and August 4 and 7, placed the *Chandra* X-Ray Observatory into its operational orbit, with initial apogee and perigee altitudes of 140 and 10 Mm, respectively.

During the orbital transfer period, the science instrument teams activated and began functional checks of the High-Resolution Camera (HRC) and of the Advanced CCD Imaging Spectrometer (ACIS). Also during this period (on July 26), bake-out of the ACIS began, with its door to the optical cavity of the telescope still closed so that any molecular contamination would vent to space. After approximately 2 weeks (on August 8), the *Chandra* Operations Control Center (OCC) opened the ACIS door by remote command. Then, on 1999 August 12, the OCC opened the telescope’s (forward contamination cover) sunshade door, the last barrier between the *Chandra* focal plane and the X-ray sky.

When the sunshade door opened, the attitude control system was not yet in its normal operating mode. Although the aspect camera was acquiring data, it was not yet an active part of the attitude control system. Rather, the *Chandra* gyroscopes, which have very small drift, were controlling the spacecraft’s attitude. Further, the dither mode, which moves the image around in a small focal plane region (to avoid focusing onto a single pixel) was not yet active. Consequently, the pointing was already very stable, even without aspect camera data. However, the absolute pointing was uncertain by up to $10^\circ$, because the fine attitude of the spacecraft had not yet been established.

As *Chandra*’s first celestial X-rays reflected off its precision mirrors, the ACIS-S (spectroscopy array) lay in the focal position, with the telescope’s aim point on CCD S3, one of two back-illuminated devices of the 10 CCDs comprising the ACIS focal plane. The *Chandra* science team had selected this as the at-launch configuration, in case the translation table failed to operate. Likewise, the at-launch configuration of the focus mechanism placed S3 near best focus, based on X-ray testing at the Marshall Space Flight Center (MSFC) X-Ray Calibration Facility (XRCF).

With X-rays falling onto the active ACIS detector, the *Chandra* science team obtained the observatory’s first image, a 9 ks observation using ACIS CCDs S2, S3, I0, I1, I2, and I3. It is impossible to convey the excitement and tension that accompanied this observation, as the image of the first photons appeared on a display at the OCC. The *Chandra* Project, which had its formal origins in an unsolicited 1976 proposal (Principal Investigators: R. Giacconi and H. Tananbaum) to NASA, was 23 years in the making. Everyone present at the OCC keenly felt the exhilaration of witnessing these efforts come to fruition.

After several minutes, the accumulated ACIS image (Fig. 1) showed a few photons concentrated within a few arcseconds of each other, not too far (about $5^\prime$) from the optical axis. This immediately demonstrated that *Chandra*’s mirrors were performing as expected and that the telescope was not far from best focus. The clustering of photons was from the brightest source in the field. To acknowledge the enormous contributions to *Chandra* by the telescope scientist Leon Van Speybroeck, the project scientist (M. C. W.) dubbed this first source Leon X-1.

The *Chandra* team next pointed the observatory toward the radio-loud quasar PKS 0637−752 ($z = 0.654$), selected for on-orbit checkout and imaging optimization. After bore sighting and focusing the telescope, the *Chandra* ACIS obtained the first publicly released image on August 15, showing the discovery of an...
X-ray jet in this quasar (Schwartz et al. 2000). On August 19, Chandra obtained the official “first-light” image (released on August 26; Tananbaum 1999; Hughes et al. 2000; Pavlov et al. 2000), a spectacular view of the supernova remnant Cassiopeia A (Cas A), revealing a central candidate neutron star.

Here we present an analysis of those data obtained during the true “first light”—the image of the first Chandra field and its brightest source, Leon X-1. First (§ 2), we describe the Chandra observation and analyses of the X-ray data. Next (§ 3) we present and discuss visible-light spectroscopy of Leon X-1 obtained at the European Southern Observatory. We conclude (§ 4) with a discussion of the multiwavelength properties of Leon X-1 in the context of the eigenvector-1 (E1) correlation space for active galactic nuclei (AGNs).

2. CHANDRA OBSERVATION AND DATA ANALYSIS

The first Chandra observation (ObsID 62568) lasted 9 ks and used ACIS CCDs S2, S3, I0, I1, I2, and I3 in the timed-exposure mode, with the standard 3.241 s frame time. During the observation, the aspect camera tracked six stars that it had acquired during a full-field search. This was unique in that the aspect stars were selected autonomously, rather than by ground command. In addition, the initial on-board attitude estimate differed by approximately 7" from the true attitude. Consequently, we prepared special input files for a custom run of the aspect data-processing pipeline to produce an aspect solution. This solution showed that the observatory was pointed at approximately $\alpha_{2000} = 5^h19^m34^s$ and $\delta_{2000} = -60^\circ 43' 11'$. However, this position was still uncertain by several arcseconds because the observation was performed without tracking the aspect fiducial lights, which enable precise registration of the science instrument focal plane relative to the telescope boresight. Hence, we fine-tuned the aspect solution (§ 2.1) using accurately known positions of optical counterparts obviously identified with X-ray sources in the field.

We used Chandra X-ray Center (CXC) processing (CXCDS 6.2.4) to create level-2 event lists. For finding X-ray sources, we selected events in pulse-invariant (PI) channels corresponding to 0.5–8.0 keV for the front-illuminated CCDs (S2; I0–I3) and to 0.25–8.0 keV for the back-illuminated CCD (S3). Due to uncertainties in the low-energy response, we used only data in the range 0.5–8.0 keV for the spectral analyses. During the observation, there were no instances of increased background. Following a discussion (§ 2.1) of our analysis of the X-ray image, we describe (§ 2.2) the results of X-ray spectrometry of these sources and then summarize (§ 2.3) their X-ray properties.

2.1. Image Analysis

We employed source-finding techniques described in Swartz et al. (2003), with a circular Gaussian approximation to the point-spread function and a minimum signal-to-noise ratio (S/N) of 2.6, resulting in significantly fewer than one expected accidental detection in the field. The corresponding background-subtracted point-source detection limit is about 10 counts, corresponding to a 0.5–8.0 keV flux of about $7 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$ for an unabsorbed power law of photon index $\Gamma = 1.5$. The algorithm found 15 sources—1 on S2, 10 on S3 (Fig. 1), and 4 on the (4 CCD) I array. That most of the detected sources were on S3 is not surprising, in that this (back illuminated) CCD included the aim point and also has the deepest sensitivity of the ACIS CCDs because of its superior low-energy response.

2.1.1. X-Ray Source Positions

After detection of the sources, we immediately noticed a systematic offset of about 5" between several of the X-ray sources and their respective candidate visible-light counterparts in the United States Naval Observatory Catalog USNO-B1.0 (Monet et al. 2003, hereafter USNO-B1), one a 7th magnitude star also detected with the aspect camera. In order to fine-tune the aspect solution, we minimized the separation between the X-ray and visible-light positions (§ 2.1.2) using a position error–weighted least-squares fit, treating the right ascension, declination, and roll angle of the pointing position as free parameters. For the visible-light positions, we adopted uncertainties from the USNO-B1 catalog. For the X-ray positions, we used uncertainties given by $1.51(\sigma^2/N + \sigma^2)^{1/2}$, where $\sigma$ determines the size of the circular Gaussian that approximates the point-spread function at the source location, $N$ is the aperture-corrected number of source counts, $\sigma_s$ is a systematic error, and the factor 1.51 scales the radius to enclose 68% of the circular Gaussian. For various values of $\sigma_s$, ranging from 0 to 0.4, we allowed $\delta$ R.A., $\delta$ decl., and $\delta$ roll to vary freely. Once we applied the resulting offsets to the initial X-ray positions, all fits were excellent, independent of the choice for $\sigma_s$. Uncertainties in the plate scale imply a systematic uncertainty of 0.1. Given that, where relevant, the USNO and Chandra positions agree to high precision, we believe that 0.2 is a reasonable and conservative estimate for $\sigma_s$. We note that the precise value of $\sigma_s$ has no statistically significant impact on the positions of the X-ray sources.

Table 1 lists positions of the 15 detected X-ray sources, with corresponding extraction radius, net counts, S/N, and X-ray positional uncertainty. The field’s brightest X-ray source, S3-5, is the source we nicknamed Leon X-1. Table 1 also gives the X-ray flux and the separation between each X-ray source and any candidate counterpart (§ 2.1.2) in the USNO-B1 or in the Two Micron All Sky Survey (2MASS).

8 See http://asc.harvard.edu/cal/Hrma/optaxis/platescale.
radius (by searching around the X-ray position within a 99% confidence listed in Table 1. We selected non–X-ray candidate counterparts alogs for candidate counterparts centered on the X-ray positions

9 See http://heasarc.gsfc.nasa.gov/db-perl/W3Browse/w3browse.pl.

Using the HEASARC cf eature, we searched available catalogs for candidate counterparts centered on the X-ray positions listed in Table 1. We selected non–X-ray candidate counterparts by searching around the X-ray position within a 99% confidence radius ($r_{99}$, 3.03/1.51 times the X-ray positional uncertainty $\sigma_X$)

2.1.2. Search for Counterparts

Using the HEASARC cf eature, we searched available catalogs for candidate counterparts centered on the X-ray positions listed in Table 1. We selected non–X-ray candidate counterparts by searching around the X-ray position within a 99% confidence radius ($r_{99}$, 3.03/1.51 times the X-ray positional uncertainty $\sigma_X$)

2.1.2.1. USNO

Table 2 lists the positions of candidate visible-light counterparts (with two candidates for source I-3). There are 2446 USNO-B1.0 sources within a 12' radius centered on the X-ray pointing

### Table 1

| Designation | Source | $r_{99}$ (arcsec) | N/S | Flux (15) | USNO (arcsec) | 2MASS (arcsec) |
|-------------|--------|------------------|-----|-----------|---------------|---------------|
| J051903.8–604401 | S3-1 | 3.0 | 8.5 | 2.8 | 0.69 | 6 | 0.9 |
| J051907.1–604500 | S3-2 | 2.9 | 11.0 | 3.0 | 0.61 | 8 |
| J051912.0–604359 | S3-3 | 2.1 | 27.7 | 4.6 | 0.39 | 20 |
| J051917.9–603316 | S3-16 | 1.5 | 32.2 | 4.5 | 1.55 | 6 |
| J051932.6–604619 | S3-4 | 2.4 | 21.6 | 4.5 | 0.43 | 15 |
| J051936.3–604804 | S3-5 | 4.2 | 1974.0 | 41 | 0.31 | 680 |
| J051935.2–604142 | S3-6 | 1.5 | 83.2 | 7.6 | 0.32 | 59 |
| J051958.2–604533 | S3-7 | 2.9 | 22.2 | 4.5 | 0.48 | 16 |
| J051959.9–604759 | S3-8 | 5.3 | 17.7 | 3.8 | 0.82 | 13 |
| J052003.7–604316 | S3-9 | 2.8 | 16.4 | 3.8 | 0.51 | 12 |
| J052028.2–604648 | S3-10 | 8.3 | 165 | 7 | 11 | 0.49 |
| J052031.5–604002 | IA-1 | 8.7 | 15.3 | 3.2 | 1.37 | 6 |
| J052126.0–604405 | IA-2 | 21.0 | 19.7 | 4.3 | 0.69 | 15 |
| J052169.6–604100 | IA-3 | 22.0 | 64.3 | 6.8 | 1.68 | 20 |
| J052144.5–602918 | IA-4 | 59.0 | 94.7 | 6.9 | 3.65 | 6 |

* Source extraction radius.
* Approximate number of source counts (after background subtraction).
* Detection S/N.
* X-ray position uncertainty (1 $\sigma$ radius, as discussed in the text).
* X-ray (0.5–8.0 keV) flux in units of $10^{-15}$ ergs cm$^{-2}$ s$^{-1}$.
* Separation between X-ray position and cataloged position of candidate counterpart.
* Discussed in the text.
* brightest source in the first Chandra field, dubbed Leon X-1.

### Table 2

| X-Ray Source | USNO | 2MASS | Difference |
|--------------|------|-------|------------|
| (1)          | (2)  | (3)   | (4)        |
| (2)          | (5)  | (6)   | (7)        |
| (8)          |      |       |            |
| S3-1         | 79.766284 | -60.733748 | 0.0089 | ... | ... | 0.0234 | ... |
| S3-2         | ... | ... | 0.0072 | ... | ... | 0.0189 | ... |
| S3-3         | ... | ... | 0.0029 | ... | ... | 0.0075 | ... |
| S3-4         | ... | ... | 0.0039 | ... | ... | 0.0093 | ... |
| S3-5         | 79.901437 | -60.801170 | 0.0008 | 79.901378 | -60.801132 | 0.0047 | 0.17 |
| S3-6         | 79.930200 | -60.695042 | 0.0029 | ... | ... | 0.0077 | ... |
| S3-7         | ... | ... | 0.0044 | ... | ... | 0.0115 | ... |
| S3-8         | ... | ... | 0.0127 | ... | ... | 0.0333 | ... |
| S3-9         | 80.015428 | -60.721203 | 0.0050 | 80.015043 | -60.721169 | 0.0131 | 0.69 |
| S3-10        | 80.117506 | -60.779848 | 0.0046 | 80.117507 | -60.779869 | 0.0122 | 0.08 |
| IA-1         | 80.132063 | -60.666987 | 0.0359 | ... | ... | 0.0943 | ... |
| IA-2         | ... | ... | 0.1647 | ... | ... | 0.4329 | ... |
| IA-3         | 80.320806 | -60.683301 | 0.0534 | ... | ... | 0.1403 | ... |
| IA-4         | 80.319622 | -60.683301 | 0.0534 | ... | ... | 0.1403 | ... |
| IA-5         | 80.2537 | ... | ... | ... | ... | 0.6665 | ... |

* Average number of accidental coincidences expected in the region searched.
* Difference between USNO and 2MASS coordinates of candidate counterparts.
* Not searched because of nonnegligible probability for accidental coincidence $N_{99}$. 
direction, corresponding to $1.5 \times 10^{-3}$ USNO sources arcsec$^{-2}$. Based on this sky density, column (4) of Table 2 gives the expected number $N_{99}$ of accidental USNO coincidences within $r_{99}$ of each X-ray source. The probability of getting one or more matches by chance is given by the Poisson probability, $(1 - e^{-N_{99}}) \rightarrow N_{99}$ for $N_{99} \ll 1$. In most cases (9 of 16), these probabilities are below 1%. For the two X-ray sources most off-axis, namely, IA-2 and IA-4, the probability for accidental identification exceeded 10%. Consequently, we chose not to search for USNO counterparts for these two sources. Column (8) of Table 1 gives the separation between each X-ray source and its USNO candidate, where we found one. We note that the candidate optical counterpart to source S3-10 is a 7th magnitude A3 V star. Due to its brilliance, other viable counterpart candidates may be hidden (see § 2.3.2).

2.1.2.2. 2MASS

We found (Table 2) three candidate 2MASS counterparts. There are 6427 2MASS sources within a 12$''$ radius centered on the X-ray pointing direction, corresponding to $3.9 \times 10^{-3}$ 2MASS sources arcsec$^{-2}$. Based on this sky density, column (7) of Table 2 gives the $N_{99}$ of accidental 2MASS coincidences within $r_{99}$ of each X-ray source. Similar to our search of the USNO catalog, we chose not to search for 2MASS counterparts to the four X-ray sources most off-axis, namely, IA-2, IA-3, and IA-4.

Tables 1 and 2 list additional pertinent information about potential infrared counterparts. Column (9) of Table 1 gives the separation between each X-ray source and its 2MASS candidate, where we find one. Column (8) of Table 2 gives the separation between visible-light and infrared candidates for those X-ray sources having both USNO and 2MASS candidates. In these three cases, USNO-2MASS separations are subarcsecond, indicating that the visible-light and infrared sources are the same object.

Table 3 gives the near-infrared magnitudes and colors of the three 2MASS candidate counterparts. Figure 2 shows a near-infrared color-color diagram of 2MASS objects within the Chandra field, including the three candidate counterparts. The 2MASS colors for the A3 V star (Table 3), the counterpart to S3-10, are consistent with its stellar classification. However, the other two 2MASS candidate counterparts do not lie on the main sequence, independent of the amount of absorption (reddening). These two objects, counterparts to S3-5 (Leon X-1) and to S3-9, have similar infrared colors, consistent with those of an unobscured AGN. Indeed, spectroscopy of Leon X-1 (§ 3.1) at the European Southern Observatory (ESO) confirms that it is a type 1 AGN at $z = 0.3207$.

2.1.2.3. Other X-Ray Observations

We also used the HEASARC "browse" feature to search for other X-ray observations of the Chandra sources. Only various Röntgensatellit (ROSAT) catalogs yielded positional coincidences within 0.5 arcsec: The possible faint ($9.9 \pm 3.9 \times 10^{-3}$ counts s$^{-1}$) source 1RXS J052145.5–602906 lies about 14" from IA-4; the bright ($6 \pm 1 \times 10^{-2}$ counts s$^{-1}$) source 1RXS J051934.0–604800, about 16" from Leon X-1. Because of uncertainties in the ROSAT positions, these separations are consistent with the respective ROSAT and Chandra sources being the same in each case.

2.2. X-Ray Spectral Analysis

For each source for which we performed a detailed spectral analysis, we obtained source counts and then a spectrum from within the appropriate extraction radius (Table 1). To estimate background for the spectral analysis discussed here, we created one data set each for S2, S3, and the I array, removing all events within 10 times the respective extraction radius of each source, and inferred the average background per square arcsecond. For S3 the rate was $2.2 \times 10^{-6}$ counts s$^{-1}$ arcsec$^{-2}$.

For the spectral analysis, we employed CIAO version 3.0.2 to extract the PI files and used CXC CALDB 2.2.5 calibration files (gain maps, quantum efficiency uniformity, and effective area) to generate effective area and response functions. We grouped the data to ensure at least 15 counts per spectral bin and restricted the energy range to 0.5–8.0 keV, due to uncertainties in the ACIS spectral response at lower energies. In calculating interstellar absorption, we utilized tbabs (available in XSPEC$^{10}$ ver. 11.2) with default abundances and cross sections (Wimbs et al. 2000). Except where indicated, all quoted errors on spectral parameters are extrema on the two-interesting-parameter, 68% confidence contours.

We were able to obtain informative spectral fits (§ 2.2.1) for the brightest X-ray source in the field and less informative spectral fits (§ 2.2.2) for the next brightest. For the remaining (fainter) X-ray sources, we could only determine three-band X-ray colors (§ 2.2.3).

2.2.1. X-Ray Spectrum of S3-5 (Leon X-1)

Only the brightest source, S3-5 (Leon X-1), had sufficient counts to warrant a serious spectral analysis. Because this source

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$^{10}$ See http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec.
was about 5′ off-axis, its image was sufficiently blurred that we safely ignored effects of pileup (<5%). These data, obtained shortly after opening the telescope’s forward cover, preceded any damage to the front-illuminated CCDs from low-energy protons scattered from the X-ray mirrors onto the ACIS focal plane during radiation belt passage. (Since this radiation problem was understood, ACIS has always been stowed—out of focal position—during radiation belt passages.) Furthermore, accumulated molecular contamination on the ACIS optical-focal position—during radiation belt passages.)

Although neither the blackbody model nor the MEKAL model with solar abundances gave an acceptable fit, a two-temperature MEKAL model did: χ² = 54 on 57 degrees of freedom, with best-fit temperatures 0.25 ± 0.04 and 4.6 ± 1.9 keV. The higher temperature component accounted for 82% of the flux, accounting for the absence of lines and similarity to a thermal bremsstrahlung model. As with the power-law fit, the two-temperature MEKAL fit requires negligible interstellar absorption, N_H/(10²² cm⁻²) = 0.0+0.4−0.0, for four interesting parameters.

2.2.2. X-Ray Spectrum of S3-10

The next brightest source, S3-10, had only about 160 counts, which we grouped into spectral bins of at least 15 counts each. With χ² = 10 on 4 degrees of freedom, a power-law fit was marginally unacceptable at 95% confidence. Blackbody and MEKAL models each yielded an acceptable fit, but with very different values for all parameters (Table 4) except the flux.

2.2.3. X-Ray Color-Color Relation

The remaining 13 Chandra sources had fewer than 100 detected source counts each; thus, we attempted no spectral fitting for them individually. However, to estimate the flux (Table 1) of each (faint) source on S3 (1–4 and 6–9), we fit their co-added spectra for them individually. However, to estimate the flux (Table 1) of each (faint) source on S3 (1–4 and 6–9), we fit their co-added spectra to an absorbed power law. This fit yielded a spectral index of 1.45 and a column of N_H/(10²² cm⁻²) = 0.07. We then scaled the flux of each source proportionally to its detected counts. For each S3 source, we also determined count rates in three X-ray bands, which Figure 5 displays in an X-ray color-color diagram.

2.3. Summary of X-Ray Properties

To conclude the discussion of the X-ray observation of the first Chandra field, we summarize the X-ray properties of the detected sources.

2.3.1. S3-5 (CXOU J051936.3−604804)

With a (0.5−8 keV) flux of 6.8 × 10⁻¹³ ergs cm⁻² s⁻¹, source S3-5 (Leon X-1) was by far the brightest X-ray source in the first Chandra field. For a sky density of about two such sources per square degree (Kim et al. 2004), it was somewhat fortuitous that so bright a source lay in the initial field of view (0.12 deg²) and on CCD S3 (0.02 deg²). We have identified this X-ray source with a 17th B-magnitude type 1 AGN at redshift z = 0.3207 (§ 3.2). Based on its X-ray spectrum (§ 2.2.1; Fig. 3) and redshift (§ 3.2), the 0.5−8 keV (rest frame) luminosity of Leon X-1 is about 2 × 10⁴⁴ ergs s⁻¹ (H₀ = 70 km s⁻¹ Mpc⁻¹, Ω_m = 0.3, and Ω_Λ = 0.7).
colors (Fig. 5) are correct, its spectrum is much harder than any other source on S3, possibly indicating a very high absorption column. This and the absence of either a USNO or 2MASS candidate counterpart are consistent with a highly obscured AGN.

2.3.6. Other X-Ray Sources

The remaining sources detected on CCD S3 have X-ray colors (Fig. 5) similar to those of S3-5 and S3-9. Thus, it is tempting to argue that these X-ray sources are also (unobscured) type-1 AGNs. Based on the large number of AGNs observable with Chandra (e.g., Kim et al. 2004), this conclusion is reasonable.

3. VISIBLE-LIGHT SPECTROSCOPY OF LEON X-1

Using spectrographs of the European Southern Observatory (ESO) at La Silla (Chile), we obtained visible-light spectroscopy of the candidate counterpart to the field’s brightest X-ray source (S3-5, Leon X-1). We briefly describe (§ 3.1) those spectroscopic observations and then discuss (§ 3.2) the results.

3.1. Spectroscopic Observations

For the spectroscopy, we used both the ESO Multi-Mode Instrument imaging spectrograph (EMMI; § 3.1.1) and the ESO Faint Object Spectrograph and Camera (EFOSC2; § 3.1.2). Due to different capabilities of the two instruments, the two observations were complementary (§ 3.1.3).

3.1.1. EMMI Spectrum

We used the EMMI to obtain a spectrum of Leon X-1 (Fig. 6), on the morning of 2004 March 23. The EMMI grism used for this observation spans 3100–9000 Å with a 2.86 Å pixel dispersion and 8 Å (full width at half maximum [FWHM]) resolution. Initially, the primary purpose of the EMMI spectrum was to determine the redshift. Consequently, we utilized available telescope time to obtain a 1800 s exposure at an air mass greater than 4. In order to minimize effects of differential refraction at large air mass, we obtained the spectrum at the parallactic angle, i.e., with dispersion direction parallel to horizon. Furthermore, we corrected the spectrum for average atmospheric extinction using Cerro Tololo Inter-American Observatory (CTIO) coefficients and calibrated the flux using two reference stars albeit at relatively low air mass (1.03 and 1.18). We estimate that chromatic errors in the line flux measurements are less than 5%–10% longward of 4500 Å.

3.1.2. EFOSC2 Spectrum

In order to achieve somewhat better resolution and S/N, we also observed Leon X-1 with the EFOSC2 at the 3.6 m telescope on the night of 2005 January 20. Under clear conditions and <1.5 seeing, we obtained three 2200 s exposures at a median air mass of 1.25. These spectra span 6300–8200 Å at 5.2 Å (5.6 pixel) FWHM resolution, with a 20–30 S/N in the continuum. After flattening, 6% fringing in the red part of the spectrum remained; however, this does not significantly affect any emission line. We flux-calibrated the combined spectrum (Fig. 7) against a standard star (HD 60753, spectral type B2 III) reduced identically. This calibration also corrects for flux lost through the 1′′ wide entrance slit.

3.1.3. Comparison of EMMI and EFOSC2 Spectra

The EMMI and EFOSC2 spectra are complementary in that the former spans a broader spectral range, whereas the later is of higher quality. There are some cross-calibration uncertainties between the two spectra, obtained with different instruments under differing conditions. Thus, we scaled the EMMI spectrum upward so
**Fig. 6.**—EMMI flux-calibrated spectrum of Leon X-1, with identification of the strongest emission lines. Circled crosses mark the strongest telluric (terrestrial) absorption features. The dotted curve shows a pure Fe	extsc{ii} template spectrum (Véron-Cetty et al. 2004), redshifted ($z = 0.3207$) and sampled at the dispersion of the EMMI spectrum.

**Fig. 7.**—EFOSC2 flux-calibrated spectrum of Leon X-1, with identification of the strongest emission lines. Circled crosses mark the strongest telluric (terrestrial) absorption features. The dotted curve shows a pure Fe	extsc{ii} template spectrum (Véron-Cetty et al. 2004), redshifted ($z = 0.3207$) and sampled at the dispersion of the EFOSC2 spectrum.
that the flux of the narrow Hβ component matched that in the higher quality EFOSC2 spectrum. However, this flux scale factor was only 1.1, and there were no significant differences in the wavelength calibrations.

3.2. Spectroscopic Results

The extensive spectral coverage of the EMMI spectrum includes numerous emission lines—forbidden lines and narrow and broad permitted lines—as identified in Figure 6. Based on observed wavelengths of the Hα and [O II] λλ4959, 5007 lines, we obtain a redshift of 0.3207 ± 0.0004. Furthermore, the blue continuum and broad permitted lines indicate little line-of-sight obscuration to the broad-line region. Consequently, we classify Leon X-1 as a type 1 AGN, consistent with its power-law X-ray spectrum exhibiting little intrinsic absorption. Within its wavelength range, the EFOSC2 spectrum (Fig. 7) shows the same features as the (wider range) EMMI spectrum, with somewhat better spectral resolution and higher S/N.

In the remainder of this section, we describe our analysis of the EMMI and EFOSC2 spectra of Leon X-1—fits to the observed emission lines (§ 3.2.1), the Fe ii line complex (§ 3.2.2), a relative blueshift of higher ionization forbidden lines (§ 3.2.3), and the hydrogen Balmer decrement (§ 3.2.4). The following section (§ 4) then investigates these results in terms of the multwavelength properties of AGNs.

3.2.1. Emission-Line Fits

We fit recognized emission lines with Gaussian profiles, after estimating the continuum under each line or each set of simultaneously fitted lines. Each of the stronger permitted lines clearly exhibits a narrow core and extended wings, which we fit with double (broad and narrow) Gaussian components. The spectra also show several emission-line blends, e.g., Fe ii λ4924 with Hβ (λ4861), Fe ii λ5018 with [O II] λλ4959, 5007, and [O II] λλ4363 with Hγ (λ4342). Table 5 lists the fitted emission-line parameters—rest and observed wavelengths, redshift, FWHM, line flux, and flux ratio to Hβ (narrow) and to Hγ (broad) components—for the EMMI spectrum; Table 6, for the EFOSC2 spectrum. Where possible, we used the (higher quality) EFOSC2 data to model better blended lines (Table 6).

The FWHMs of the two strongest broad lines, Hα and Hβ, are about 4000 km s⁻¹ (Table 5). Those of the other (weaker) broad lines scatter about this value (Tables 5 and 6), being generally less accurate due to lower signal and to blending. The FWHMs of the narrow Balmer components are 1000–1500 km s⁻¹; those of the remaining lines, all forbidden lines and the narrow component of He i λ5876, are smaller. Except for a possible blue extension in each line of the [O II] λλ4959, 5007 doublet, no line departs significantly from Gaussian, within limits imposed by line blending and S/N.

3.2.2. Fe ii Line Complex

The complexes of permitted Fe ii lines, thought to originate through resonance fluorescence and collisional excitation (e.g., Osterbrock 1989), are among the strongest components of the visible-light emission-line spectra of unobscured AGNs (Wills et al. 1985). The EMMI spectrum of Leon X-1 (Fig. 6) displays at least two strong Fe ii emission blends, near 6000 Å (4500 Å) and near 7000 Å (5300 Å) in the observed (rest) frame, the second being affected by strong telluric absorption near 6800 Å. The first blend comprises lines mainly from Fe ii multiplets 37 and 38; the second, from multiplets 48 and 49 (e.g., Phillips 1976; references therein). For comparison, Figures 6 and 7 show the (arbitrarily scaled) template Fe ii spectrum of I Zw 1 (compiled by Véron-Cetty et al. 2004); redshifted and rebinned as appropriate for Leon X-1 with no additional broadening. Of importance for fitting lines, Fe ii λ4924 and Fe ii λ5018 (from multiplet 42) blend with Hβ and the [O II] λλ4959, 5007 doublet. Notably, the flux of the Fe ii complex around 4500 Å (rest) is strong, as discussed below (§ 4).
While its strongest forbidden lines are the \([\text{O} \text{iii}]\) \(\lambda\lambda 4959, 5007\) doublet, the spectrum of Leon X-1 exhibits several high-ionization forbidden lines, \([\text{Fe} \text{vi}]\) and \([\text{Ne} \text{v}]\), that are characteristic of a hot or a photoionized environment, such as that of an AGN. Typical AGN lines that are not detected in Leon X-1 include \([\text{O} \text{i}]\) \(\lambda\lambda 6300\) and \([\text{S} \text{ii}]\) \(\lambda 4067\). While its strongest forbidden lines are the \([\text{O} \text{iii}]\) \(\lambda\lambda 4959, 5007\) doublet, the spectrum of Leon X-1 exhibits several high-ionization forbidden lines, \([\text{Fe} \text{vi}]\) and \([\text{Ne} \text{v}]\), that are characteristic of a hot or a photoionized environment, such as that of an AGN. Typical AGN lines that are not detected in Leon X-1 include \([\text{O} \text{i}]\) \(\lambda\lambda 6300\) and \([\text{S} \text{ii}]\) \(\lambda 4067\). There is slight evidence for weak \([\text{N} \text{ii}]\) \(\lambda 6583\), but the fit is not well constrained because of its superposition over the broad and bright wing of \(H\alpha\).

Interestingly, the higher ionization forbidden lines are blueshifted relative to the permitted lines, as well as to the low-ionization forbidden lines. Figure 8 shows a correlation of relative blueshift of each detected forbidden line, with its critical density for collisional de-excitation. In that no stellar or interstellar absorption features are evident, we assume a systemic redshift of \(z = 0.3207\) (\S 3.2).

Other authors (e.g., Pelat et al. 1981) have noted such a correlation for other AGNs, inferring that the higher ionization forbidden lines probably originate in photoionized clouds between the broad-line and the narrow-line regions. Thus, their relative proximity to the nucleus would result in higher velocities and ionization parameters relative to the those of the narrow-line regions.

![Fig. 8.—Plot of relative redshift of each forbidden line against its critical density for collisional de-excitation. Plotted redshifts are relative to a systemic redshift of \(z = 0.3207\), with 1 \(\sigma\) errors displayed. Critical densities are those for \(T = 10^4\) K (Appenzeller & Ostreicher 1988). The gray symbol for the \([\text{Fe} \text{x}]\) line indicates a marginal detection.](image)

However, such Seyfert galaxies usually display significant line profile asymmetries toward the blue, implying both outflow and extinction of emission from the far hemisphere of the AGN. In contrast, most line profiles for Leon X-1 are symmetric, with only \([\text{O} \text{iii}]\) \(\lambda 4959, 5007\) showing a weak asymmetry (\S 3.2.1). This argues against a spherically symmetric outflow (e.g., Appenzeller & Ostreicher 1988), but would be consistent with bipolar ejection, if radiation from receding material is suppressed, e.g., extinguished, while that from approaching material is not.

### 3.2.4. Hydrogen Balmer Decrement

The Leon X-1 spectrum shows a prominent hydrogen Balmer sequence, from \(H\alpha\) through \(H\gamma\). Generally interpreted as recombination emission lines from photoionized gases near the AGN’s core, their relative strengths provide diagnostics of physical conditions in these regions. Our analysis of the Leon X-1 spectrum finds a Balmer decrement \(H\alpha, H\beta, H\gamma, H\delta / H\beta\) of \([1.56, 0.41, 0.33]\) and \([3.79, 0.40, 0.18]\), respectively, for the broad-line and the narrow-line series (Table 5). Photoinization-recombination models (e.g., Osterbrock 1989 and references therein) typically give \(H\alpha, H\beta, H\gamma / H\beta\approx [3, 0.5, 0.3]\), for the (unreddened) decrement. For Leon X-1, the observed decrement for the narrow-line Balmer sequence is consistent with this case and a small amount of reddening (cf. Fig. 1 in Osterbrock et al. 1963).

Unlike the narrow-line Balmer decrement, the broad-line decrement is inconsistent with standard photoionization-recombination cases (A and B; Osterbrock 1989) for any value of the reddening. For the broad-line component in Leon X-1, the measured \(H\alpha / H\beta\approx 1.6\). Systematic uncertainties in our observations, e.g., due to line blending and calibration errors, might raise this ratio to about 2.0, still significantly below the canonical value for a tenuous photoionized plasma. Furthermore, this ratio (\(H\alpha / H\beta\approx 1.6\)) is unusually small compared to that found in other AGNs (e.g., Vaughan et al. 2001). Reddening, of course, can only steepen the decrement and thus cannot account for so low an \(H\alpha / H\beta\) ratio. Other effects, self-absorption in the Balmer lines, collisional excitation and de-excitation, stimulated emission, etc., can also alter the Balmer decrement (Osterbrock et al. 1963; Capriotti 1964; Cox & Mathews 1969; Gerola et al. 1971; Parker 1964; Adams & Petrovian 1974; Netzer 1975, 1977; Krolik & McKee 1978; Ferland & Rees 1988; Rees et al. 1989; Zheng & Puetter 1990). These studies (especially Krolik & McKee 1978; Drake & Ulrich 1980; Zheng & Puetter 1990) indicate that the most favorable conditions for producing a flat Balmer decrement are nonnegligible optical depths in \(H\alpha\) and high densities, which

### Table 6

Emission Lines in the EFOSC2 Spectrum of Leon X-1

| Emission Line  | Rest \(\lambda\) (Å) | Observed \(\lambda\) (Å) | \(z\) | FWHM \(\text{km s}^{-1}\) | Flux \((\text{ergs s}^{-1} \text{cm}^{-2})\) | \(F/F(H/\beta)\) |
|---------------|---------------------|------------------------|-----|-----------------|----------------------|----------------|
| \([\text{H} \beta]\) | 4861 | 6418.1 | 0.3203 | 1236.44 | 3.65 \(\pm\) 0.31 | 1.00 \(\pm\) 0.07 | 0.30 \(\pm\) 0.05 |
| \([\text{He} \text{ii}]\) | 4861 | 6423.3 | 0.3214 | 3757.95 | 12.22 \(\pm\) 0.06 | 3.35 \(\pm\) 0.13 | 1.00 \(\pm\) 0.11 |
| \([\text{O} \text{iii}]\) | 4959 | 6584.9 | 0.3206 | 6211.23 | 12.51 \(\pm\) 0.09 | 0.34 \(\pm\) 0.05 | 0.10 \(\pm\) 0.01 |
| \([\text{S} \text{ii}]\) | 5007 | 6612.3 | 0.3206 | 5287.7 | 2.59 \(\pm\) 0.07 | 0.71 \(\pm\) 0.08 | 0.21 \(\pm\) 0.02 |
| \([\text{Fe} \text{vi}]\) | 5721 | 7550.0 | 0.3197 | 4777.69 | 0.16 \(\pm\) 0.04 | 0.02 \(\pm\) 0.01 | 0.01 \(\pm\) 0.00 |
| \([\text{He} \text{ii}]\) | 5876 | 7757.1 | 0.3201 | 5377.34 | 0.15 \(\pm\) 0.06 | 0.04 \(\pm\) 0.02 | 0.01 \(\pm\) 0.00 |
| \([\text{He} \text{ii}]\) | 5876 | 7760.8 | 0.3208 | 2587.4 | 2.10 \(\pm\) 0.19 | 0.59 \(\pm\) 0.09 | 0.17 \(\pm\) 0.03 |
| \([\text{Fe} \text{vi}]\) | 6087 | 8031.7 | 0.3195 | 4822.34 | 0.32 \(\pm\) 0.04 | 0.09 \(\pm\) 0.02 | 0.03 \(\pm\) 0.00 |

- \(a\): Broad component of double Gaussian fit denoted by subscript \(B\); narrow, by subscript \(N\).
- \(b\): Rest-frame FWHM, corrected for instrumental resolution.
- \(c\): Flux in units of \(10^{-15}\) ergs s\(^{-1}\) cm\(^{-2}\).
- \(d\): Propagated statistical fitting error combined with estimated systematic uncertainty.
increase collisional de-excitation, driving the hydrogen level population toward local thermodynamic equilibrium. In the extreme, these conditions produce a very flat Balmer decrement, as observed in the spectra of cataclysmic variable accretion disks (Williams 1983; Elitzur et al. 1983; Williams & Shipman 1988).

Consequently, the broad-line Balmer decrement observed in Leon X-1 suggests emission from dense photoionized gas in which collisional de-excitation is nonnegligible. While the emitting gas could be in cloudlets circulating in the inner region of the AGN, it could also comprise the photosurface of an accretion disk (see also Collin-Souffrin et al. 1981, 1982). If we accept the large black hole mass and high accretion rate inferred from our analysis below (§4), this broad-line emitting gas may reside in the distal region of the accretion disk that fuels the UV/X radiation from black holes.

4. PROPERTIES OF LEON X-1 IN THE CONTEXT OF THE E1 CORRELATION SPACE

Analyses of multiwavelength parameters of AGNs show correlations among widths and strengths of Hβ, [O iii] λ5007, and Fe ii optical emission lines, and soft X-ray photon index. A remarkable feature of the E1 correlation space in a principal-component analysis (Boroson & Green 1992, hereafter BG92; Wang et al. 1996; Sulentic et al. 2000b) is that radio-loud (RL) and radio-quiet (RQ) AGNs occupy very different regions in the E1 projected planes (Sulentic et al. 2003). The proposed physical drivers for these correlations are supermassive black hole mass, accretion rate, and system orientation. Furthermore, a recent study (Zamanov & Marziani 2002) has shown that these same correlations apply to stellar-mass accreting systems, e.g., interacting binaries in which the accretor is a white dwarf. In view of the apparent robustness of the E1 correlation space, we use it in examining the X-ray, visible-light, and radio data for Leon X-1, in order to estimate its black hole mass and accretion rate.

In the BG92 sample, the broad-line Hβ FWHM is typically 11,000–20,000 km s\(^{-1}\) for RL AGNs, but much smaller—mean \(\approx 2000 \text{ km s}^{-1}\)—for RQ AGNs (Sulentic et al. 2000a, 2000b). Sulentic et al. (2000a, 2000b) categorize RQ AGNs with somewhat larger broad-line H\(\beta\) FWHMs (3000–4000 km s\(^{-1}\)) as “population A.” For these population A RQ AGNs, the mean equivalent width (standard deviation) of broad-line H\(\beta\) emission is EW(H\(\beta\)) \(\approx 128 \text{ Å (40 Å)}\); that of [O iii] λ5007 is EW([O iii] λ5007) \(\approx 20 \text{ Å (20 Å)}\). Sulentic et al. (2002) also find the mean (standard deviation) absolute B magnitude of the population A RQ AGNs in the BG92 sample to be \(M_B = -22.3(1.8)\). We find that the corresponding parameters for Leon X-1, FWHM(H\(\beta\)) \(\approx 3757 \text{ km s}^{-1}\), EW(H\(\beta\)) \(\approx 118 \text{ Å}, EW([O iii] λ5007) \approx 26 \text{ Å}, and \(M_B \approx -24\), are characteristic of a population A RQ AGN.

On the other hand, the other two E1 parameters, namely, the soft X-ray photon index \(\Gamma\) and the strength of the Fe ii complex at 4570 Å, reveal that Leon X-1 is not a typical population A RQ AGN. In particular, we find \(\Gamma = 2.05^{+0.11}_{-0.09}\), versus the BG92 sample population A mean (standard deviation) of \(\Gamma = 2.6(0.1)\) (Sulentic et al. 2000a).

However, the steep mean photon index found for the BG92 sample is based on ROSAT data (0.3–2.4 keV) and largely reflects the soft excess common in low-redshift (\(z < 0.4\)) quasars (Porquet et al. 2004). The mean hard photon index (2–12 keV) for a sample of 40 PG quasars based on XMM-Newton spectra is 1.89 ± 0.11 (Piconcelli et al. 2005), fully consistent with our measured value. Leon X-1 is therefore somewhat unusual in the absence of a soft excess.\(^{13}\)

In addition, we find EW(Fe ii λ4570) = 160 Å for Leon X-1, versus EW(Fe ii λ4570) = 60 Å (16 Å). AGNs with EW(Fe ii λ4570) larger than 100 Å are rare (Lipari et al. 1993; Grupe et al. 1999). Ultrastrong Fe emitters are typically broad absorption line (BAL) QSOs or strong infrared Seyfert 1 galaxies (e.g., Hartig & Baldwin 1986; Zheng et al. 2002; Yuan & Wills 2003). Such strong Fe ii emission may result either from a high accretion rate onto a very massive central accretor or from active star formation.

Comparison of Leon X-1 with the BG92 AGN sample in the principal correlation planes of the E1 space (Fig. 1 in Sulentic et al. 2000b) confirms that it is distinguishable from other AGNs primarily because of its strong Fe ii emission. Leon X-1 is among the population A RQ AGNs with the largest EW(Fe ii) and EW(Fe ii)/EW(H\(\beta\)) population A3/A4 in the optical parameter plane of the E1 space (see Sulentic et al. 2002). However, the strength of the [O iii] lines relative to the H\(\beta\) broad component is more similar to population A1/A2 RQ AGNs and narrow-line Seyfert-1 galaxies (cf. Fig. 6 for Leon X-1 with Fig. 2 in Sulentic et al. 2002).

Figure 9 plots Leon X-1 in the EW(Fe ii λ4570)/EW(H\(\beta\)) plane, along with a model grid from Zamanov & Marziani (2002). The grid coordinates correspond to values (Fig. 9 caption) of the accretor mass and the mass-scaled (bolometric) luminosity, i.e., the effective accretion rate, for a model of accretion onto a black hole. Applying this parameterized model to Leon X-1, we would infer a black hole mass exceeding \(10^7 M_\odot\), and an effective accretion rate \(10^3 L_\odot/M_\odot\), only about a factor of 3 below the Eddington limit. If we take these values as representative, the bolometric luminosity of Leon X-1 would be about \(5 \times 10^{46} \text{ ergs s}^{-1}\).

\(^{13}\) This observation was taken with a focal plane CCD temperature of \(-90 \text{ C}\), prior to any measurements of the internal calibration source. The CCD gain in this configuration is therefore not well calibrated. However, even a substantial error in the gain would not affect the power-law index or the lack of an observed soft excess.
for a $10^9 M_\odot$ accretor, 200 times greater than the 0.5–8 keV X-ray luminosity we observed. Reconciling these luminosities would require that most of the bolometric luminosity from Leon X-1 lie outside the X-ray band. For a $10^9 M_\odot$ black hole accreting at a rate similar to our estimate for Leon X-1, the peak of the accretion disk spectrum lies below 30 eV (see, e.g., Fig. 7.6 in Krolik 1999).

The multiwavelength properties of Leon X-1 are unusual compared to those of more common AGNs. Some of these differences might result from a rare combination of large black hole mass, a high accretion rate, and perhaps active star formation. In the context of E1 correlation space, Leon X-1 is an outlier, together with PG 1351+236, PG 0043+038, Mrk 231, and 0759+651 (see Fig. 1 of Marziani et al. 2001). The four sources were found to show substantial mid- and far-IR emission and a significant rise toward the far-IR, suggesting significant contribution from circumstellar star formation. The excess of Fe ii in Leon X-1, as in Mrk 231 and 0759+651, in comparison with other BL QSOs, requires additional excitation processes. One possible mechanism is the shocks associated with star formation. Leon X-1 has the optical properties of a type 1 AGN, and this could be the rare situation where the central quasar is “dusty,” as well as “naked,” as pointed out by Haas et al. (2000). We also note that the star formation in such AGNs could be caused by jet-induced cloud collapse as per Saxton et al. (2005). In this case the induction of star formation by quenching of the jets/outflow (usually associated with high L/M) provides an explanation for strong radio emission from the source.

In summary, Leon X-1 is a rather extreme system among RQ AGNs. Our multiwavelength data suggest that it may be a very massive black hole accreting at a rate close to its Eddington limit. However, the absence of significant internal absorption does not evidence a dense outflow, which would be expected for such a system. Furthermore, the observed X-ray luminosity is less than 1% of the bolometric model implied by the model. Alternatively, starburst activity might account for some of its extreme properties. Broadband IR/visible/UV observations would help to address these issues.

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We dedicate this paper to his memory.