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A SEARCH FOR FAR-ULTRAVIOLET EMISSION LINES FROM DIFFUSE HOT GAS IN THE HALO OF NGC 4631

HENRY C. FERGUSON[1]
Space Telescope Science Institute, Baltimore, MD 21218; ferguson@stsci.edu
W. VAN DYKE DIXON AND ARTHUR F. DAVIDSEN
Department of Physics and Astronomy, Johns Hopkins University, Charles and 34th Streets, Baltimore, MD 21218; wvd, afd@pha.jhu.edu
AND
RALF-JUERGEN DETTMAR
Astronomisches Institut, Ruhr-Universitaet Bochum, Universitätsstrasse 150/ NA 7, D-44780 Bochum, Germany; dettmar@wsa.astro.ruhr-uni-bochum.de
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ABSTRACT

During the Astro-2 mission in 1995 March, the Hopkins Ultraviolet Telescope (HUT) was used to conduct a sensitive search for far-UV emission lines from hot gas in the halo of NGC 4631. This galaxy has strong radio continuum emission, extended Hα emission, and soft X-ray emission from an extended halo. Recent *ROSAT* observations indicate that much of the X-ray emission comes from a very soft component, with a temperature less than 6×10^5 K. Gas cooling through this temperature range should show emission in the prominent O VI $\lambda\lambda$1032, 1038 and C IV $\lambda\lambda$1548, 1551 lines. Hot gas interacting with cold clouds at the interface of the disk and the halo may form turbulent mixing layers, which should produce strong emission in lower ionization species such as C II λ1335 and O III] $\lambda\lambda$1661, 1666.

The aperture of the HUT spectrograph subtends 10″ × 56″ and was positioned parallel to the disk 39″ (1.4 kpc) south of the nucleus. No emission lines were detected. The derived constraints are tempered somewhat by the unknown extinction within the NGC 4631 halo. If it is low, the upper limits suggest that the mean mixing-layer temperatures are less than 2×10^5 K or that mixing layers are not a significant contributor to the observed Hα emission at the position of the HUT slit. For smooth flows, the upper limit to the O VI flux suggests that less than approximately 15 $M_\odot$ yr^{-1} are processed through a galactic fountain in NGC 4631.

Subject headings: galaxies: halos — galaxies: individual: NGC 4631— galaxies: spiral — ultraviolet: galaxies

1. INTRODUCTION

Highly ionized diffuse gas constitutes a major component of the interstellar medium (ISM) of a spiral galaxy. Much of this gas is thought to be heated and ejected into the halo by the combined effects of supernovae in the disk (Spitzer 1956; Shapiro & Field 1976; Bregman 1980; Norman & Ikeuchi 1989). A variety of physical processes governs the circulation of hot gas through the halo, including shock heating by supernovae, photoionization by hot stars in the disk and the extragalactic background, heating by cosmic rays, entrainment by magnetic fields, and turbulent mixing with cold clouds. While tracing the circulation of the hot gas is of great importance for understanding galactic evolution, direct constraints on the distribution of hot gas and the physical conditions in it are extremely difficult to obtain. The distribution at temperatures of approximately 10^5 K has been partially mapped by absorption-line studies of C IV, Si IV, and N V, which suggest that hot gas does pervade the halo, with scale heights of 4.9 kpc for the gas responsible for C IV absorption and possibly smaller values for N V (Savage & de Boer 1979, 1981; Sembach & Savage 1992; Savage et al. 1993). The detection of O VI in absorption toward extragalactic sources provides additional evidence for hot gas in the halo (Davidsen 1993; Hurwitz & Bowyer 1995). Further evidence comes from the detection of diffuse C IV emission at high Galactic latitudes, which combined with the absorption-line column densities suggests pressures for $T \sim 10^5$ K gas of $2200 \leq P/k \leq 3700$, electron densities $0.01\ \mathrm{cm}^{-3} \leq n_e \leq 0.02\ \mathrm{cm}^{-3}$, and filling factors $0.5\% \leq f \leq 5\%$ (Martin & Bowyer 1990; Shull & Slavin 1994). Strong emission from O VI is predicted from gas cooling from $T > 10^6$ K to the lower temperatures that produce the C IV emission. There currently exist only upper limits to the diffuse O VI emission, the most restrictive suggesting a line ratio $I(\mathrm{O\ VI})/I(\mathrm{C\ IV}) \lesssim 5$ (Edelstein & Bowyer 1993).

Studies of halo gas in our own Galaxy are inevitably hindered by the fact that the measurements integrate along a line of sight through the disk as well as the halo. Edge-on galaxies are good candidates to search for emission from a hot galactic corona. During the Astro-2 mission the Hopkins Ultraviolet Telescope (HUT) was used to conduct a sensitive search for far-UV emission lines at a position 39″ (1.4 kpc) off the plane of NGC 4631. This spiral galaxy has strong radio continuum emission, has extended Hα emission, has soft X-ray emission from an extended halo, and is in a direction of low foreground extinction. It is therefore an ideal place to search for halo gas.

2. OBSERVATIONS AND DATA ANALYSIS

NGC 4631 was observed twice with HUT (Davidsen et al. 1992) during the Astro-2 mission in 1995 March. The observations were obtained during orbital night through a 10″ × 56″ aperture. After editing out portions of the data near sunrise, the total exposure time was 3058 s. NGC 4631 is located at high Galactic latitude ($b = 84°$), has low foreground reddening, $E(B - V) = 0.03$, and has an inclination angle of 85°

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[1] Hubble Fellow.

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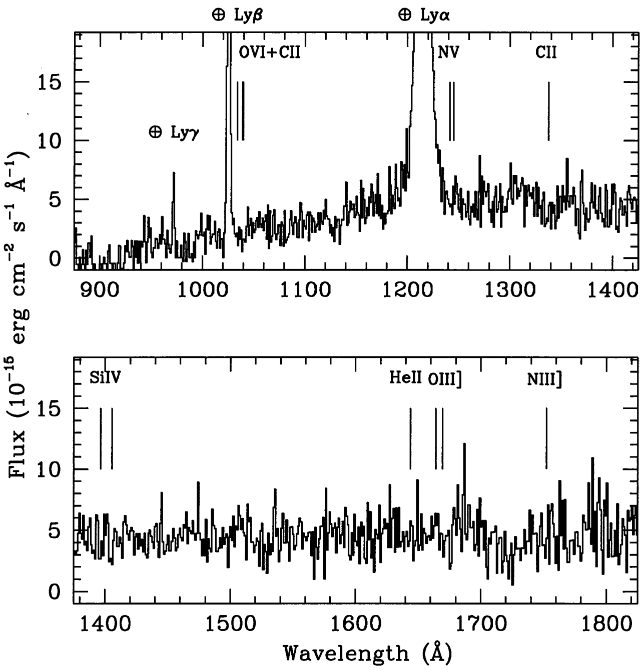

FIG. 1.—Spectrum of the halo of NGC 4631, with positions of expected emission lines marked. The only emission features seen are from terrestrial airglow.

(Weliachew, Sancisi, & Guélin 1978; Hummel & Dettmar 1990). The aperture was placed parallel to the disk (position angle 86°) at a location 39″ south of the nucleus. This corresponds to 1.4 kpc for an adopted distance of 7.5 Mpc (Rand, Kulkarni, & Hester 1992). The position of the aperture center is determined from the guide stars to an accuracy of about 2″. Details of the HUT spectrometer and its calibration for Astro-2 are given by Kruk et al. (1995). The spectrum obtained spans the wavelength range from 820 to 1840 Å at a resolution of about $R = 400$.

The reduced spectrum is shown in Figure 1. Conversion to flux involves a correction for dark count, a correction for the overlap of second and first order at (first order) wavelengths longer than 1824 Å, and division by the (time-dependent) sensitivity curve computed from observations of hot white dwarfs (Kruk et al. 1995). The emission features seen in the spectrum are all attributable to airglow in Earth's upper atmosphere. The continuum is probably due to stars in the halo and thick disk, with some contribution from nebular continuum. We have not yet attempted to model its spectral energy distribution.

No emission lines other than terrestrial airglow were detected. Our emission-line upper limits are determined directly from the raw spectrum. Using χ^2 fits, we determine the mean continuum level at the position of each line. Total counts vary from 6 to 14 per pixel. The FWHM of the airglow lines through the $10'' \times 56''$ slit is typically 8 pixels (1 pixel = 0.51 Å), so we may safely use Gaussian statistics. For single lines, we compute the number of counts within 8 pixels that would correspond to a signal-to-noise ratio of 2 and multiply by a factor of 1.32 to account for flux that would have fallen outside the 8 pixel region. For overlapping multiplets, we use box sizes that encompass both lines and modify the correction factor accordingly. The number of pixels used and the resulting upper limits in raw counts are shown in Table 1. To convert to flux, we use the nominal effective area curve of Kruk et al. (1995) and correct for the time-dependent variation in detector sensitivity. This correction varies from 5% at long wavelengths to 20% at the position of the O VI doublet. Our fluxes are further corrected for foreground extinction using the Cardelli, Clayton, & Mathis (1989) extinction curve, adopting $E(B - V) = 0.03$ and $R_V = 3.1$.

The integrated Hα flux in the HUT slit is 1.68×10^{-13} erg cm^{-2} s^{-1}, determined from a calibrated optical image provided by R. Rand (Rand et al. 1992), shown in Figure 2 (Plate L1). Registration of the optical image and the HUT aperture position was based on the known offset from a guide star, visible just above the galaxy in the Hα image, that was used to center the HUT aperture. The integrated H I column density at the position of the HUT slit is estimated to be roughly 5×10^{21} cm^{-2} from the maps of Rand & van der Hulst (1993). This high column density introduces rather large uncertainties in the extinction because of dust along the line of sight *within* NGC 4631, discussed further below.

3. DISCUSSION

3.1. *Constraints on Smooth Galactic Fountain Models*

Halo gas is thought to originate from gas in the disk that has been shock heated to temperatures greater than 10^6 K by supernova blast waves. The gas rises into the halo, where, in the absence of further heating, it radiatively cools and falls back onto the plane. Several authors have computed the spectrum of the cooling gas (e.g., Edgar & Chevalier 1986; Shapiro & Benjamin 1993). For such steady state models, the strongest predicted feature is O VI λλ1032, 1038. We can convert our limits on O VI to limits on the amount of mass

TABLE 1

2 σ UPPER LIMITS TO REDSHIFTED EMISSION-LINE FLUXES

FEATURE	$N_{\rm pix}$	COUNTS	FLUX (10^{-15} erg cm^{-2} s^{-1}) Observed	FLUX (10^{-15} erg cm^{-2} s^{-1}) Dereddened	SPECIFIC INTENSITY (10^{-7} erg cm^{-2} s^{-1} sr^{-1})
O VI λ1034........	16	24.0	7.61	10.94	7.54
C II λ1037.........	8	20.6	6.52	9.35	6.45
N V λ1240	12	31.6	8.07	10.55	7.28
C II λ1335.........	8	28.0	7.20	9.21	6.36
Si IV λ1400........	16	32.5	8.87	11.24	7.75
C IV λ1550........	12	26.8	9.15	11.49	8.15
He II λ1640.......	8	23.6	10.65	13.33	9.20
O III] λ1663.......	16	26.4	12.55	15.67	10.81
N III] λ1750.......	8	21.8	12.81	15.89	10.96

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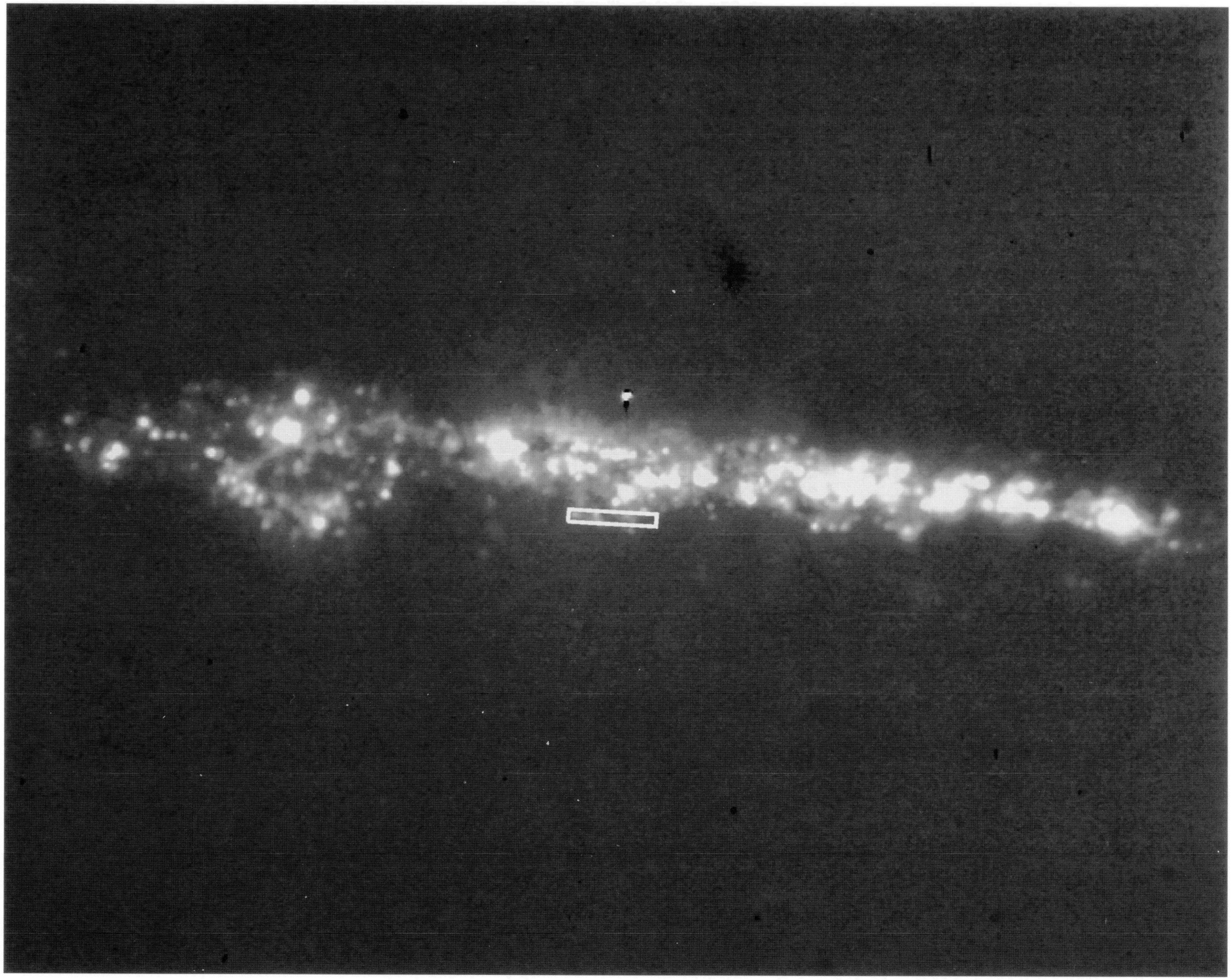

FIG. 2.—Position of the HUT aperture superposed on an Hα image of NGC 4631. The aperture is located 1.4 kpc south of the disk and subtends 0.4 × 2 kpc. North is up in the image, and east is to the left.

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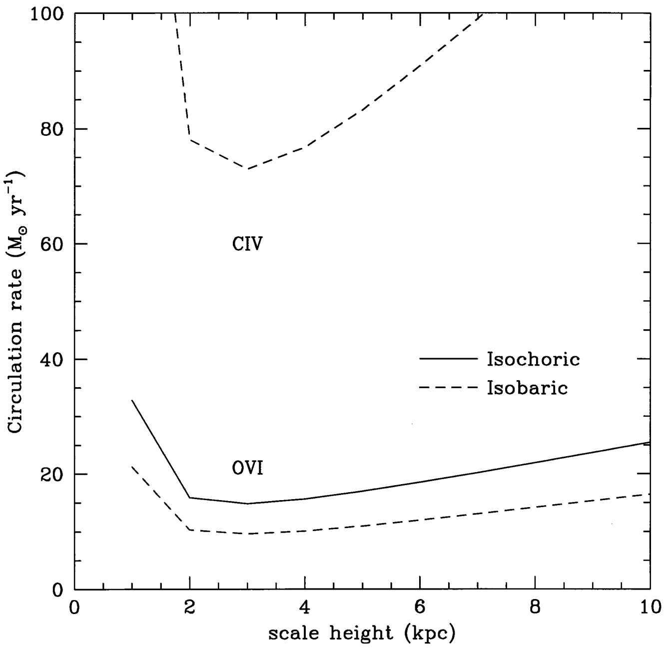

FIG. 3.—Upper limits to the mass flux through the NGC 4631 halo, computed from the models of Edgar & Chevalier (1986), as a function of the pressure scale height of the O VI and C IV emitting gas. The mass limit derived from the C IV flux assuming isochoric cooling is about 1.5 times the isobaric limit and is thus off scale.

circulating in the halo only if we know the distribution of the gas both within the HUT aperture and throughout the halo. Consider a simple model in which the distribution of the O VI–emitting gas is uniform with radius along the disk but has an exponential distribution in the vertical direction. For such a smooth distribution, the fraction of the total emission subtended by an aperture of solid angle Ω at a projected position z kpc above the center of the disk is

$$f = \frac{2r\Omega d^2}{\pi r^2 h} e^{-2z/h}, \tag{1}$$

where d is the distance to the galaxy, r is the radius of the disk, and h is the pressure scale height in kpc. The factor of 2 in the exponent comes from the fact that the emissivity scales with the square of the pressure. From the models of Edgar & Chevalier (1986), we can compute the predicted count rate in the HUT slit as a function of h and the mass-flow rate M, and hence we derive limits on the amount of mass that could be processed through a galactic halo and still avoid detection. These are shown in Figure 3. For comparison, Martin & Bowyer (1990) estimate a mass flux in the Milky Way halo of 6–25 $M_\odot$ yr^{-1} from their observations of diffuse C IV emission.

The upper limits become considerably higher if dust is mixed in with the observed H I above the NGC 4631 disk. If we assume the H I gas is uniformly distributed with radius and has a Galactic dust-to-gas ratio, such that $N_{\rm H}/E(B-V) = 5 \times 10^{21}$ cm^{-2} mag^{-1} (Diplas & Savage 1994), then optical depths of unity are reached for O VI only 1/10 of the way through the halo. The actual mass-flow rate could thus be an order of magnitude higher than shown in Figure 3.

3.2. *Constraints on Turbulent Mixing Layers*

Because of the nonuniform nature of the ISM and the bulk flows induced by supernova winds, the physical conditions in the Galactic halo are likely to be quite turbulent. Slavin, Shull, & Begelman (1993) have proposed that turbulent mixing of hot gas with cooler gas on the boundaries of clouds could be an effective mechanism for cooling the gas and a significant contributor to the emission seen from the Galactic halo (Shull & Slavin 1994). Mixing-layer models produce [S II]/Hα line ratios in good agreement with observations of diffuse ionized gas and "interstellar froth" in Magellanic irregular galaxies and some edge-on galaxies and thus provide at least a partial answer to the problem of ionizing the Reynolds (1984, 1990) layer in our own Galaxy.

To assess the contribution of mixing layers to the halo emission in NGC 4631, we compute upper limits to the fluxes of various UV emission lines relative to Hα and compare them with the predictions of Slavin et al. (1993). These models assume that hot gas entering the mixing region has a temperature $T_h = 10^6$ K, but the NGC 4631 halo is 3 times hotter (Wang et al. 1995; see § 3.3). Raising T_h may slightly alter the resulting line ratios, an effect we ignore in our analysis. In Figure 4, we plot our upper limits as solid horizontal lines (in the case of no extinction) and as dotted lines (for dust and hot gas uniformly distributed as above). Superposed are the predicted line fluxes for mixing layers of various temperatures and shear velocities for the solar-metallicity gas from Table 1A of Slavin et al. (1993). For our Galaxy, mixing-layer models favor log $\bar{T} \approx 5.3$. At such a mean temperature, if there is no dust along our line of sight through the NGC 4631 halo, we should have detected all of the lines in Figure 4. In the more likely case that dust is mixed in with the gas, mean mixing-layer temperatures hotter than log $\bar{T} \approx 5.2$ are inconsistent with the

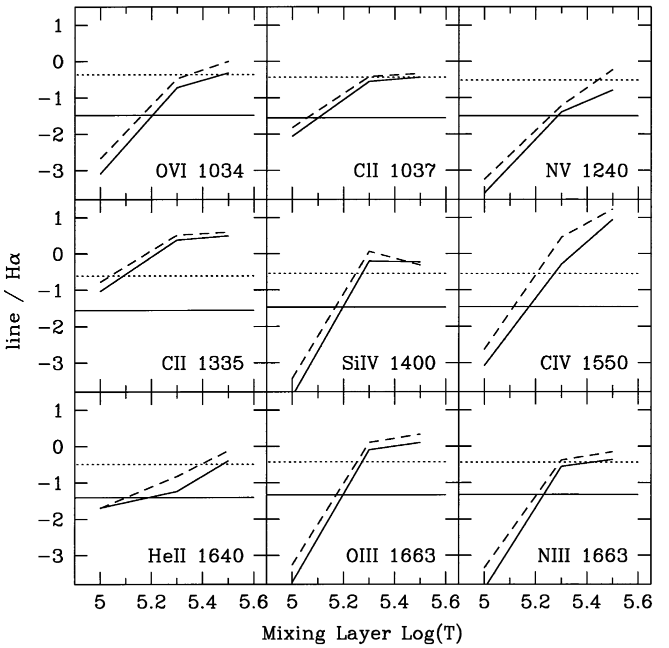

FIG. 4.—Upper limits to the intensities of selected far-UV emission lines relative to Hα, expressed as the log of the line ratio. The lower (*solid*) horizontal lines in each figure show the limits corrected only for Galactic foreground extinction. The upper (*dotted*) horizontal lines show the limits for a model in which dust is uniformly mixed with the hot gas and uniformly distributed as a function of radius along the disk. The predictions from the Slavin et al. (1993) turbulent mixing layer models are shown as a function of the mean temperature of the mixing layer log $\bar{T}$, for two values of the shear velocity. When the model curves lie above the upper horizontal lines, the emission line should have been detected.

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nondetection of C II λ1335, C IV, and O III. Alternatively, we may state the result as follows: *turbulent mixing layers with* log $\bar{T} \gtrsim 5.2$ *can account for less than 10% of the observed* Hα *flux* 1.4 kpc *above the disk of NGC 4631.*

3.3. *Where Is the Galactic Fountain?*

Because of its orientation, strong Hα emission, and strong radio halo, NGC 4631 has been a favorite target in searches for galactic fountain gas. Indeed NGC 4631 is one of the few spiral galaxies observed to have an X-ray halo. Using the *ROSAT* PSPC, Wang et al. (1995) observed diffuse X-ray emission extending more than 8 kpc above the disk. The spectrum of this halo gas shows an excess at low energies, implying a two-component thermal plasma, with a hot component at $T \sim 3 \times 10^6$ K and a cool component with a temperature less than 6×10^5 K. The total X-ray luminosity of the galaxy is surprisingly low, approximately 8×10^{39} ergs s^{-1}, corresponding to a mass flux of $\sim 1.4\ M_\odot$ yr^{-1} and accounting for only 0.3%–3% of the estimated power released by supernovae. Wang et al. (1995) hypothesize that the cooler component of the halo gas could account for up to 15% of the supernova power. Our observations fail to reveal this cooler component in either smoothly flowing gas or turbulent mixing layers. The major uncertainty is the unknown amount of dust in the H I layer at this height above the disk. If the hot and neutral gas are well mixed and uniform across the disk, and the dust-to-gas ratio is similar to that in the Milky Way, the HUT limits on steady state cooling models (Fig. 3) still allow for a significant galactic fountain. Alternatively, supernova-heated gas may simply be ejected from the galaxy.

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