X–ray Opacity in Cluster Cooling Flows

Michael W. Wise (NOAO/KPNO) and Craig L. Sarazin (UVa)

ABSTRACT. We have calculated the emergent X–ray properties for a set of spherically symmetric, steady–state cluster cooling flow models including the effects of radiative transfer. Opacity due to resonant X–ray lines, photoelectric absorption, and electron scattering have been included in these calculations, and homogeneous and inhomogeneous gas distributions were considered. The effects of photoionization opacity are small for both types of models. In contrast, resonant line optical depths can be quite high in both homogeneous and inhomogeneous models. The presence of turbulence in the gas can significantly lower the line opacity. We find that integrated X–ray spectra for the whole cooling flow are only slightly affected by radiative transfer effects. However X–ray line surface brightness profiles can be dramatically affected by radiative transfer. Line profiles are also strongly affected by transfer effects. The combined effects of opacity and inflow cause many of the lines in optically thick models to be asymmetrical.

1. Introduction

Although the detailed hydrodynamics of the gas in cluster cooling flows is somewhat uncertain, the large X–ray surface brightnesses of these systems indicate large column densities of ionized gas are present. The opacity through these columns can be large, and can have a significant impact on the emission from these objects. The idea that resonant X–ray lines in clusters might have appreciable optical depths has been noted previously by several authors.[1,2,3] Significant levels of resonant scattering can redistribute line photons spatially in the cluster, reducing the surface brightness in the center of the cluster and increasing it at larger radii. Resonant line absorption can also affect the line profiles, producing distinctive double peaked profiles. In addition, there is a growing body of evidence that cooling flows may contain considerable continuum opacity as well.[4,5,6] Recently, White et al. have reported detection of significant amounts of excess absorption associated with 12 cluster cooling flows.[6] This absorption is apparently due to photoionization. Within the cooling flow regions of clusters, the gas column densities are significantly higher than those in the surrounding cluster. The increased optical depths which these conditions imply could significantly enhance these effects. In this work, we discuss the X–ray properties for a set of cooling flow models calculated including the effects of radiative transfer. We have examined the optically thin X–ray properties for these models previously.[7].

2. Continuum Opacity

In homogeneous models, the continuum opacity due to photoionization can be appreciable, reaching values of $\tau_{ph} \sim 0.7$ in the innermost regions of the cooling flow. The total X–ray emission from this model within a radius $r \leq 1\,\mathrm{kpc}$ is reduced by $\sim 15\%$. The effects of photoionization opacity are negligible, however, for strongly inhomogeneous models. For these models, the maximum photoionization optical depths are $\sim 3 \times 10^{-3}$. Neither class of model can produce the level of absorption implied by recent observations cluster cooling flows.[6] Although the opacity due to photoionization is appreciable in the homogeneous model, this absorption is spatially confined to a fairly small portion of the cooling flow region ($r < 1\,\mathrm{kpc}$). The results of White et al. indicate that the observed absorption must cover $\sim 2/3$ of the cooling flow region.[6] However, our assumption of steady-state cooling may be inaccurate for very cool gas.

3. Line Opacity

The optical depths due to resonant line opacity are also greatly enhanced in the homogeneous models as compared to inhomogeneous ones. These calculations include the emission from 566 X–ray lines of which 235 can lead to resonant absorptions.[8,9] For an inhomogeneous cooling flow model, maximum line optical depths are typically $\sim$ 1–3, with approximately 20 lines having optical depths greater than unity. In contrast, the homogeneous model can produce $\sim$ 100 lines with $\tau_l \geq 1$ and maximum optical depths which reach values of $\sim$ 1–100. The line optical depths depend inversely on the line widths. Consequently, for any given model, the inclusion of turbulent broadening will decrease the line optical depths.

4. Emergent X–ray Properties

Radiative transfer effects can have a significant impact on the X–ray emission from cluster cooling flows. These effects are most pronounced for models with homogeneous cooling. This is due to the shell of cooler, dense material which forms just inside the sonic radius in homogeneous cooling flow models. The temperature drops catastrophically within this shell (at $r \sim 0.7$ kpc), producing a large enhancement in the amount of absorbing material. For models with distributed, inhomogeneous cooling, radiative transfer will still affect the X–ray properties but to a lesser degree.

The integrated X–ray spectra are only slightly affected by the inclusion of radiative transfer in the gas. The largest optical depths are due to resonant line scattering, which merely redistributes the emission spatially and spectrally. Because the largest optical depths are confined to number of resonance lines which produce only a small fraction of the total X-ray luminosity, the total X-ray emission is not strongly affected by transfer effects. Within the central kpc, opacity effects remove $\sim$ 15% of the total X-ray luminosity in the homogeneous model assuming thermal line broadening. At larger radii, the change is less than a few percent.

More dramatic results of radiative transfer are seen in the X–ray line surface brightness profiles. The net effect of radiative transfer is to decrease the central values of the surface brightness, and increase the brightness at larger radii. The profiles for homogeneous models show the largest effect. The effect is reduced in inhomogeneous models, but is still appreciable. Turbulent broadening reduces the level of this effect, because of the dependence of the line opacity on the line width.

Line profiles are also strongly affected by transfer effects. In optically thin, spherically symmetric cooling flow models, the lines are always symmetrical (ignoring the effects of line blending). The combined effects of opacity and inflow cause many of the lines in optically thick models to be asymmetrical.

References

1. Shapiro, P. R., & Bahcall, J. N. 1980, ApJ, 241, 1.
2. Basko, M. M. Komberg, B. V., & Moskalenko, E. I. 1981, Sov Astr, 25, 402.
3. Gil'fanov, M. R., Sunyaev, R. A., & Churazov, E. M. 1987, Sov Astr, 13, L3.
4. Lea, S. M., Mushotzky, R. F., & Holt, S. S. 1982, ApJ, 262, 24.
5. Matilsky, T., Jones, C., & Forman, W. 1985, ApJ, 291, 621.
6. White, D. A., Fabian, A. C., Johnstone, R. M., Mushotzky, R. F., & Arnaud, K. A. 1991, MNRAS, 252, 72.
7. Wise, M. W., & Sarazin, C. L. 1992, ApJ, submitted.
8. Hamilton, A. J., Sarazin, C. L., & Chevalier 1983, ApJS, 51, 115.
9. Wise, M. W. 1992, Ph.D. thesis, University of Virginia.