RADIATION HYDRODYNAMICS OF HIGH-LUMINOSITY ACCRETION INTO BLACK HOLES

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Abstract. To extend Shapiro’s (1973a, b) calculations of black hole accretion to the regimes of interstellar gas densities and of black hole masses for which emergent luminosities are expected to be high, the radiation hydrodynamics of spherically symmetric gas flows in static isotropic metrics is discussed. Since for the more luminous objects the optical depth of the accretion volume becomes large, particular attention has to be paid to radiative transfer through non-Euclidean spaces, and a method for solving the full transfer problem is presented. The method is applied to accretion into black holes of mass between $10 \ M_\odot$ and $10^5 \ M_\odot$, under the conservative assumption that all other heat sources, like dissipation of magnetic or turbulent energy, can be neglected in comparison to the compressional work term, $p \ dV$. In the interstellar gas parameter range of interest, the radiation field is then dominated by emission and absorption of synchrotron radiation from inner zones of the flow. Temperature stratifications, luminosities and emergent spectra resulting from these processes are calculated.

1. Introduction

The observational appearance of matter accreting into black holes has been the topic of numerous investigations during recent years, and several classes of astronomical objects have been proposed as possible witnesses to past occurrence of gravitational collapse. Besides the familiar X-ray binary systems, these classes include objects heretofore regarded as white dwarfs of type DC (Shvartsman, 1971) as well as strong emitters of infrared radiation located in the galactic nucleus (Shapiro, 1973b), and objects whose ‘prototype’ is BL Lac (Pringle et al., 1973).

Although it has been generally argued that conversion of gravitational potential energy into photon radiation operates most efficiently when inflow proceeds through a disk stage (cf. Novikov and Thorne, 1972), quantitative calculations of accretion hydrodynamics under the influence of radiation, as well as of the emerging spectra, have usually been, and will be in this paper, limited to the case of spherical symmetry and radial gas motion. This limitation seems rather well justified in view of the fact that the inner portions of disks are thermally unstable and tend to blow up in those regions where the signatures characteristic of black holes are produced, causing the inflow to be largely radial and omnidirectional there (Eardley et al., 1975; Pringle, 1976). Spherically symmetric calculations were presented by Shapiro (1973a,b) and by Tamazawa et al. (1975). Shapiro followed the suggestion by Kardashev (1964) that frozen-in magnetic fields play a major role in generating radiation, and computed the emission of free–free and synchrotron radiation from optically thin accreting gas.
He verified that the total luminosity increases strongly with gas density and with black hole mass such that, as remarked by Pringle et al., the objects seemingly most promising for observation tend to be optically thick over large wavelength regions since optical depth grows with both density and mass. Tamazawa et al., on the other hand, addressed themselves to the problem of high-density gas flows that are optically very thick, and found temperature stratifications that, with their assumption of frequency-independent absorption coefficients, would produce essentially black body spectra at the temperature of the interstellar gas from which the accreting material originates. While the densities in the model of Tamazawa et al., are so high as presumably to be available to black holes only in binary systems, Shapiro's results predict comparable (and higher) luminosities from accretion out of interstellar gas, at densities several orders of magnitude below Tamazawa's values. It therefore seems of interest to extend Shapiro's computations into the regime of non-vanishing optical depths, with the intention of determining the maximum luminosities that can be expected from the environment (assumed spherically symmetric) around a black hole.

As effects of optical depth come into play, the transfer of radiation has to be properly taken into account. In the present paper, an attempt is made to solve the problem of radiative transfer in conjunction with the hydrodynamics of the gas flow. To this end, a method previously applied to the determination of radiation fields in spherically symmetric stellar atmospheres is adjusted to treat problems of transfer in general isotropic metrics, and in particular the Schwarzschild metric. It is believed that this adjusted method can find several applications, among them the transport of neutrinos through collapsing high-density objects (see Yvon, 1957) and the formation of red shifted spectra on the assumption that these originate from material embedded in a spherical cloud of stars so compact that gravitational effects on photons become important (e.g. Hoyle and Fowler, 1967).

Primary attention in this paper will be focused on those spherically symmetric configurations whose emergent photon fluxes are expected to be high; for such configurations, temperature stratifications and spectra are to be determined. To this end, first the hydrodynamic equations defining the model will be given, with attention paid to the radiation terms. Then, parameter regimes of interest to the search for high-luminosity objects will be estimated and relevant emission processes will be discussed. The subsequent section will be devoted to the problem of radiative transfer through static, isotropic spaces, and the following one to the algorithm by which this problem is here to be solved. Results will be presented in the last section.

Of the several parameters that specify a configuration (such as density and temperature of the interstellar gas, mass of the black hole, accretion rate, magnetic field), only black hole mass and the relevant combination of interstellar density and temperature will be kept variable, while for the other parameters only those values most favourable to high luminosities will be considered. In particular, the magnetic field will be described in complete analogy to Shapiro's work. Such an approximate description seems justified in view of the absence of a theory of supersonic magneto-