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Linearized Gravitational Perturbations of a Kerr Black Hole: Explicit Metric Reconstruction

Abstract

The theory of gravitational perturbations of Kerr black holes has been a rich area of study for over fifty years. A significant advance was Teukolsky's discovery of a separable wave equation for linearized perturbations of the gauge-invariant Weyl curvature scalars, whose determination is usually sufficient for most purposes. However, in this new era of gravitational-wave astronomy, the reconstruction of actual metric perturbations is becoming increasingly necessary (for instance, to push perturbation theory to second order). In principle, this problem was solved by Wald, who developed a technique for reconstructing a vacuum metric perturbation from its Weyl scalars, at least at the mode level. While different parts of this lengthy procedure have been separately worked out in the literature (though only for real frequencies), the complete metric reconstruction has not yet been explicitly carried out in full generality, including for complex frequencies. We do so here by directly relating the modes of the metric perturbation (in either ingoing or outgoing radiation gauge) to the modes of either Weyl scalar. These relations make no reference to the Hertz potential (an intermediate quantity that plays no fundamental role) and involve only the radial and angular Kerr modes but not their derivatives, which can be altogether eliminated using the Teukolsky--Starobinsky identities. Our framework is also sufficiently general to handle both metric sign conventions and any normalization of the basis functions. In addition to directly connecting the physical degrees of freedom captured by the Weyl scalars to the metric perturbation---bypassing a series of complex calculations---these results should prove useful in numerical studies and for the extension of Kerr perturbation theory beyond the linear regime. We have also recently extended this procedure to case of a nonzero cosmological constant, which substantially increases the complexity of the calculation.