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Observations on the masses and mass-to-luminosity ratios of galaxies are reviewed. Mass-to-light ratios are placed on a homogeneous system to facilitate comparison among different techniques. It is concluded that galaxies are surrounded by invisible, massive envelopes that dominate the total matter of the universe. [The SC<sup>1</sup>® indicates that this paper has been cited in over 310 publications since 1979.]

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For 40 years before this review, astronomers had been arguing about invisible matter in clusters of galaxies. Fritz Zwicky of Caltech had shown in 1933<sup>1</sup> that galaxies in the nearby, rich Coma cluster were orbiting at high velocities in excess of 1,000 km s<sup>-1</sup>. If Coma was modeled as a gravitationally bound collection of galaxies, Zwicky calculated a mass needed to bind the cluster that was 10 to 100 times greater than that visible in stars. Thus the "missing mass" problem was born—excess matter in the universe that does not shine as stars and is invisible on ordinary photographs.

Subsequent studies over the next four decades confirmed and extended the problem. More groups of galaxies were studied and always with the same result—too much mass. Nevertheless, astronomers as a body were unconvinced. The idea of invisible matter was a radical one, and careful reflection showed several possible systematic errors that could spuriously inflate mass estimates—for example, the projection of nongroup members along the line of sight. The problem was an immense blockage because it meant effectively that no one could understand either the dynamics of the universe on large scales or even whether Newton's law of gravitation was universally valid.

When invited by the *Annual Review* to write on this subject in 1978, I leaped at the chance. Perhaps I was chosen because I was generally familiar with galaxies but had never previously taken a

stand on the "missing mass" problem. In 1978 there were several new developments that suggested the logjam might finally be breaking. A specific model for giant, invisible, massive halos around galaxies had been proposed by Jerry Ostriker and his colleagues<sup>2</sup> that for the first time made clear predictions about the dynamics of galaxies and galaxy clusters. A new observational tool had also emerged: rotating, neutral-hydrogen gas clouds in the outer parts of spiral galaxies, as observed with radio telescopes.<sup>3,4</sup> These hydrogen clouds extend to great distances—farther than the visible stars—and probe the mass distribution of galaxies out into the regions supposedly occupied by the invisible halos. The early data were showing high rotational velocities and excess mass there, just as the model by Ostriker *et al.* predicted.<sup>2</sup>

It therefore seemed that the data were ripe for synthesis and that an enduring statement about invisible mass in the universe might be possible. I invited my long-time collaborator Jay Gallagher to participate, and he agreed enthusiastically. Jay is a very broad astronomer who, more than most, is able to juggle many complex, competing scenarios at one time. We divided the topic in sections according to observational technique: hydrogen rotation measurements, binary galaxies, small groups, and large clusters. We were very skeptical and tried hard to argue away the evidence for invisible matter in each other's sections. Finally, each of us settled on a piece of evidence that he or she felt could not be ignored or argued away: Jay, on the dynamics of dense cores of large clusters, and I, on the outer hydrogen rotation curves of roughly two dozen spiral galaxies. With that, we both became intellectually and psychologically committed to the existence of dark matter in the universe and sat down to write a strong but reasoned statement in its favor.

The review served as a kind of watershed. Arguments stopped about whether dark matter exists and began to focus on how much there is and how it is distributed. Additional impetus soon came from particle physics, which suggested that the universe today might be filled with invisible, non-interacting elementary particles left over from the Big Bang. The marriage between astronomy and particle physics has been very fruitful and has yielded new models for galaxy and cluster formation and even the Big Bang itself.<sup>5</sup> From being an impediment to our understanding of the universe, dark matter has turned in a few short years into one of cosmology's most powerful concepts.

1. Zwicky F. Die Rotverschiebung von extragalaktischen Nebeln. *Helv. Phys. Acta* 6:110-27, 1933.

2. Ostriker J P, Peebles P J E & Yahil A. Size and mass of galaxies, and mass of universe.

*Astrophysical J.* 193:L1-L4, 1974. (Cited 185 times.)

3. Roberts M S. The rotation curves of galaxies. (Hayli A, ed.) *Dynamics of stellar systems*. Dordrecht, the Netherlands: Reidel, 1975. p. 331-40.

4. Bosma A. *The distribution and kinematics of neutral hydrogen on spiral galaxies of various morphological types*. PhD dissertation. Groningen, the Netherlands: Groningen Universiety, 1978. 186 p.

5. Blumenthal G R, Faber S M, Primack J R & Rees M J. Formation of galaxies and large-scale structure with cold dark matter. *Nature* 311:517-25, 1984.