A HISTORICAL PERSPECTIVE ON DARK MATTER

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The dominant impression which I carry away from this meeting is that extragalactic astronomy has reached a crisis ("a state of affairs in which a decisive change for better or worse is imminent", according to Fowler). The nature, origin and distribution of the dark matter and its role in galaxy formation and dynamics are issues whose resolution is likely to determine the direction of studies in galactic structure and cosmology for decades to come.

This is not the first crisis which science has encountereed, and so I thought it might be useful to ask whether there are any historical lessons from previous crises which might provide us with some solace or guidance in our present perplexed state. Fortunately this question has already been addressed, in a very influential book called *The Structure of Scientific Revolutions* by Thomas Kuhn of MIT.

The central concept in Kuhn's work is the paradigm, which he defines as a "body of intertwined theoretical and methodological belief that permits selection, evaluation and criticism". Examples of paradigms would include Newton's laws, Maxwell's equations, the caloric theory of heat, or Keynesian economics, although many paradigms are more specialized than any of these. The paradigm provides a coherent framework which suggests what experiments are worth doing, gives scientists confidence that they are on the right track, and permits selection, evaluation and criticism of both theory and experiment.

Kuhn argues that most scientists spend most of their careers doing what he calls "normal science". Normal science is work within the framework of a paradigm. It consists, not of a search for new theories—indeed, in normal science new theories are regularly suppressed—but rather of the articulation and elaboration of the paradigm. It can be thought of as puzzle-solving within a well-defined set of rules, and the motivation for doing normal science is not the desire to be useful or the drive for knowledge but rather "the conviction that, if only he is skilful enough, he will succeed in solving a puzzle that no one before has solved or solved so

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well". There may be anomalies or apparent contradictions in normal science—in fact these provide the puzzles to be solved—but the expectation of the community is that these can be resolved within the paradigm.

I believe that for the last several decades extragalactic astronomy has been normal science. The corresponding paradigm is difficult to describe fully but would include the assumptions that Newton's laws are correct, that the mass in galaxies is mostly contained in visible stars, that the initial mass function is more or less a power law and more or less the same everywhere, that galaxy formation is unbiased, etc. Many of these assumptions are not usually stated explicitly, but this is merely a sign of how deeply they are woven into the paradigm.

Not all science is normal science. According to Kuhn the regular progress of normal science is occasionally interrupted by an event which he calls a "crisis". A crisis is simply a recognition by the community that their paradigm no longer works. Examples include the distressing state of Ptolemaic astronomy at the time of Copernicus and the late nineteenth century crisis in physics caused by the photoelectric effect and the black body radiation spectrum. I would like to argue that extragalactic astronomy is in the midst of a classic Kuhnian crisis. In support of this contention, let me briefly list some of the characteristics of a crisis, taken directly from Kuhn's book.

The first sign of the crisis is that some anomaly appears to be more than just a puzzle of normal science. (From my own perspective this occurred around 1974, with the Roberts-Whitehurst rotation curve of M31 and the Ostriker, Peebles and Yahil article proposing massive halos.) The awareness of the anomaly spreads gradually throughout the community, attracting more and more attention. Eventually the most eminent scientists in the field begin to concentrate on the anomaly. (I am sure we all agree that this has happened!) As work proceeds, the unspoken assumptions of the old paradigm become stated more explicitly. (Thus we now see papers raising issues like bimodal initial mass functions, biased galaxy formation and even non-Newtonian theories of gravity.) For many scientists, discouragement and pronounced professional insecurity set in, generated by the persistent failure of the puzzles of normal science to work out as they should. (Kuhn quotes Pauli: "In any case, it is too difficult for me, and I wish I had been a movie comedian or something of the sort and had never heard of physics.") Experimenters devote themselves to finding new ways of magnifying and making explicit the breakdown of the paradigm. (For example, we have the work of Rubin and her collaborators on spiral galaxy rotation curves, Aaronson's work on mass-to-light ratios of dwarf ellipticals, and various efforts to search for faint dwarf stars in halos.) Many new paradigms are proposed, but their proponents are generally not very interested in talking to one another, since they have abandoned the old paradigm which was what they once had in common.

If, then, we are in a Kuhnian crisis, we can use the same historical evidence to predict the resolution of the crisis. According to Kuhn the time interval between the breakdown of the old paradigm and the enunciation of the new is almost always one to two decades; if we count the beginning of the present crisis from 1974 then we have less than ten years to wait. The winning theory will be difficult to recognize at first among the proliferation of new theories generated by the crisis. In particular, it usually will not explain the experimental facts much better than its predecessors, just as Copernicus's theory was no more accurate than Ptolemy's. (Thus we should not be disturbed at the shortcomings of, say, the cold dark matter scenario for galaxy formation, since it probably works about as well as Kuhn says the winning theory ought to at this point.) The new theory succeeds, not because it explains the facts so well, but because it converts a few influential scientists who are attracted for aesthetic reasons. These workers then develop and improve the theory to the point where its successes multiply and more converts are made. The final few holdouts will eventually die out, leaving a community which is once again united. The crucial observations which prove the correctness of the new theory will probably only be made long after most of the community has already accepted it. The final sign that the crisis has been resolved will be a series of textbooks which incorporate the new paradigm.

Finally, Kuhn stresses that the scientists who eventually devise the successful new theory of dark matter will almost certainly be either very young or very new to the field. However, this does not excuse you from reading any future papers I may write on this subject.