

Title: Nature of Science

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URL: <http://pirsa.org/04080003>

Abstract: <span>A personal reflection on some fascinating scientific questions that worry Prof. Smolin.</span>

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The Pioneer Anomaly:

FIG. 2: Doppler residuals as a function of time of the best fit model. The top panel shows the independent confirmation of the Pioneer 10 anomalous acceleration.

Craig B. Markwardt,\*

*a* is approximately  $a_0$

astro-ph/0104064, 0208046

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FIG. 1: NASA photo of PIONEER 10 with caption: "The Pioneer 10 probe during a checkout with its launch vehicle at the launch pad at Cape Kennedy." Pioneer 9 became Pioneer 10.

Study of the anomalous acceleration of Pioneer 10 and 11

John D. Anderson,<sup>1,2</sup> Philip A. Lubin,<sup>3</sup> Eric L. Lau,<sup>4</sup> Anthony S. Lin,<sup>5</sup> Michael Martin Nieto,<sup>6,7</sup> and Steven G. Tretyakov<sup>8</sup>

FIG. 7: An OGP plot of the early unmodeled accelerations of Pioneer 10 and Pioneer 11, from about 1981 to 1989 and 1977 to 2000, respectively [75].

FIG. 8: Unmodeled accelerations of Pioneer 10 and Pioneer 11, from about 1981 to 1989 and 1977 to 2000, respectively [75].

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# The Pioneer Anomaly:

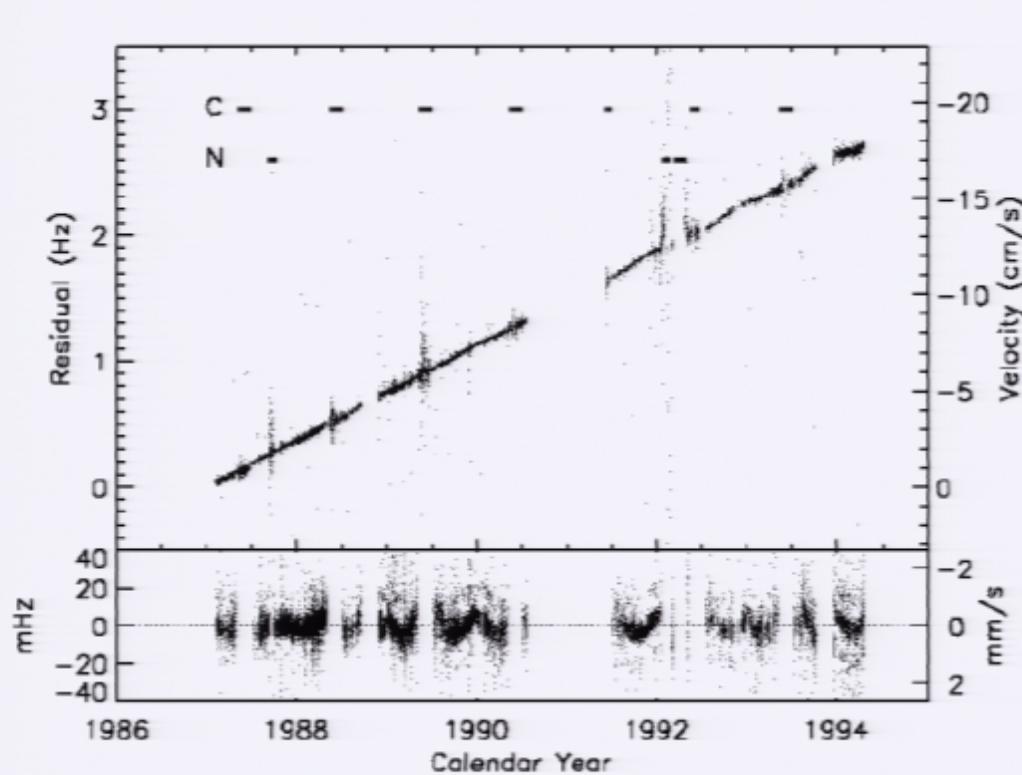


FIG. 3: Doppler residuals as a function of time of the best fit model. The top panel shows the

## Independent Confirmation of the Pioneer 10 Anomalous Acceleration

Craig B. Markwardt,\*

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*a is approximately  $a_0$*

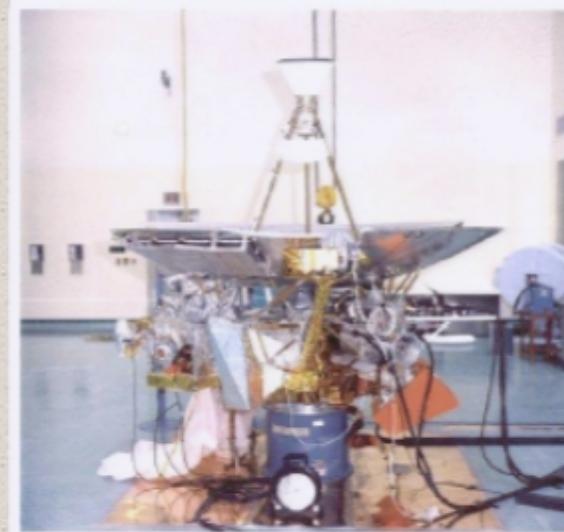


FIG. 1: NASA photo #72HC94, with caption "The Pioneer F spacecraft during a checkout with the launch vehicle third stage at Cape Kennedy." Pioneer F became Pioneer 10.

Study of the anomalous acceleration of Pioneer 10 and 11

John D. Anderson,<sup>\*a</sup> Philip A. Laing,<sup>b</sup> Eunice L. Lau,<sup>b</sup>  
Anthony S. Lin,<sup>b,c</sup> Michael Martin Nieto,<sup>b,d</sup> and Slava G. Turyshev<sup>\*e</sup>

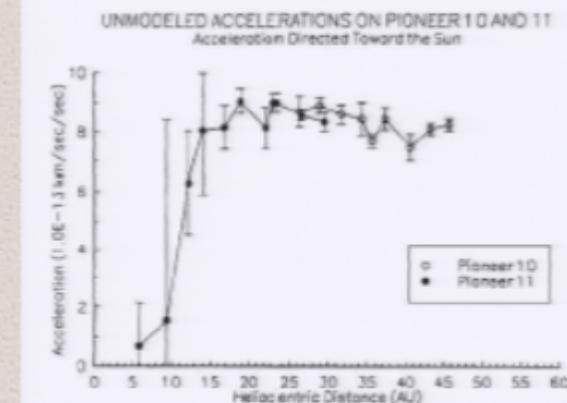
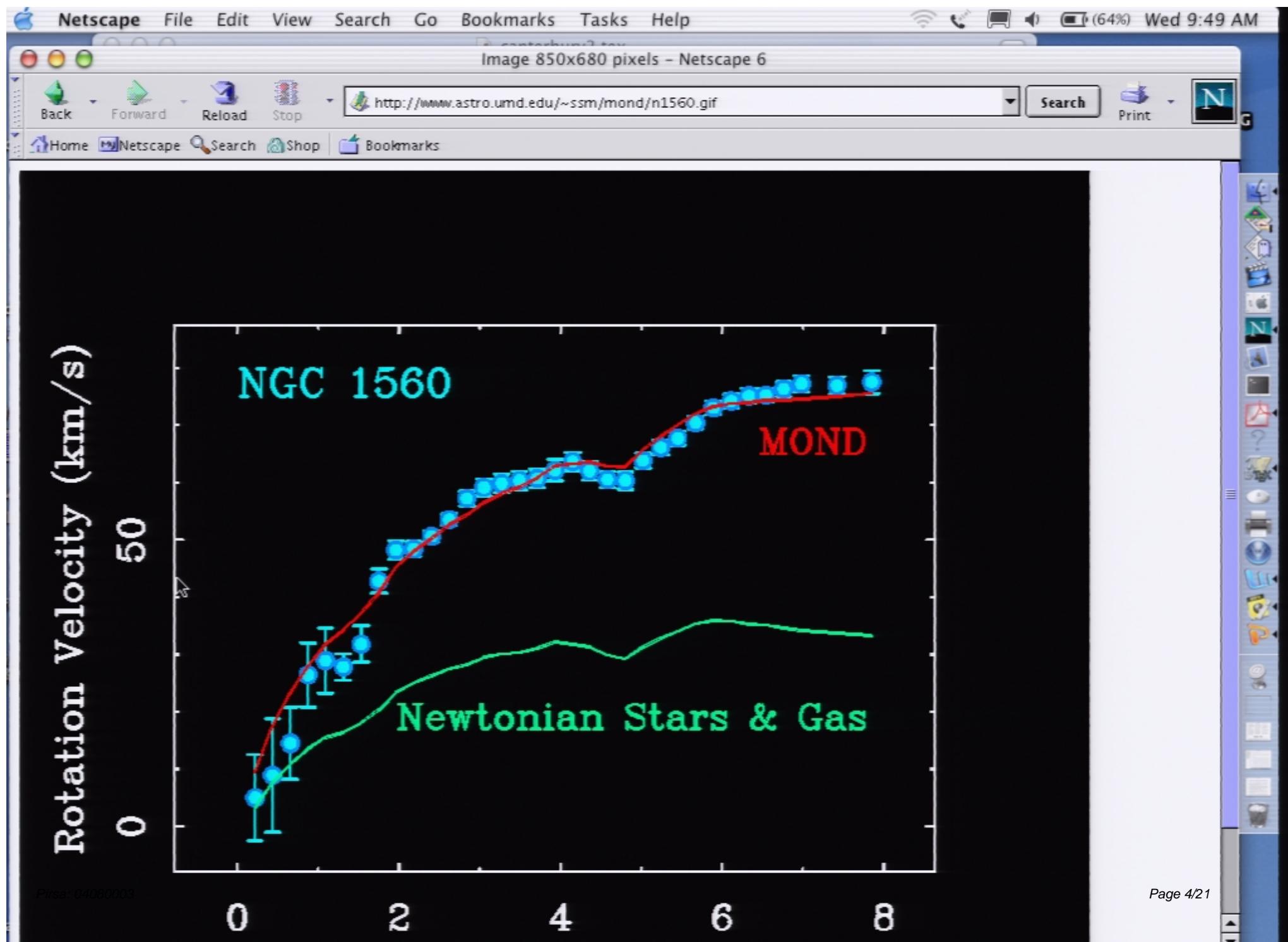
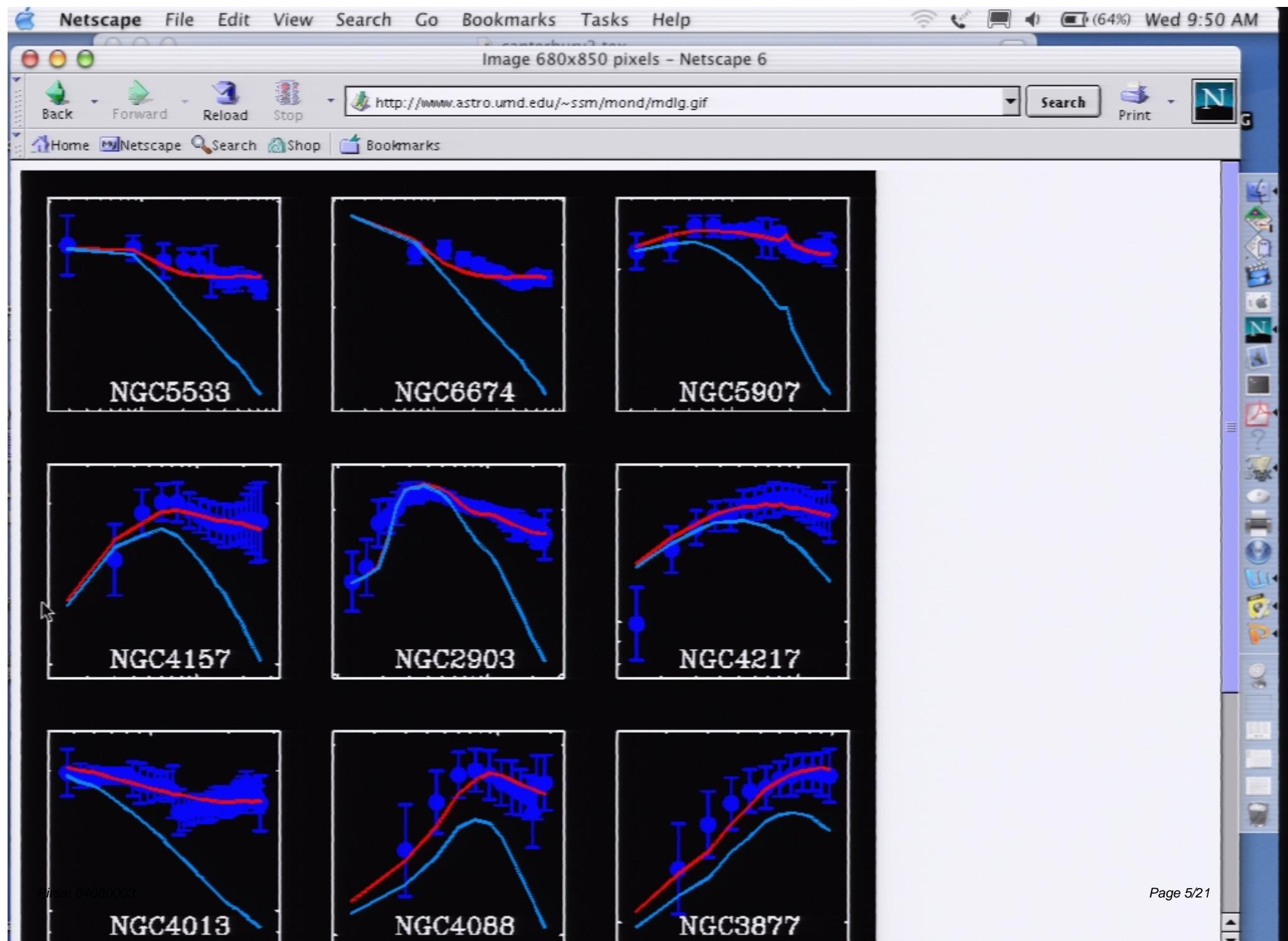


FIG. 7: An ODP plot of the early unmodeled accelerations of Pioneer 10 and Pioneer 11, from about 1981 to 1989 and 1977 to 1989, respectively [75].





Evidence for the new scale in very low energy astrophysics:

The Tully Fischer Relation:

- Galaxies have flat rotation curves, with velocity  $V$ .
- Total luminosity  $L$

astro-ph/0204521

$$CL = V^a \quad a=3.9 \pm 0.2$$

- $K = L/M$  (M-total mass)

$$CKM = V^4$$

- $CK$  should be prop to  $G$

- $CK = Ga_0$

$$a_0 = 1.2 \cdot 10^{-8} \text{ cm/sec}^2$$

$$= \sqrt{\Lambda} c^2/6$$

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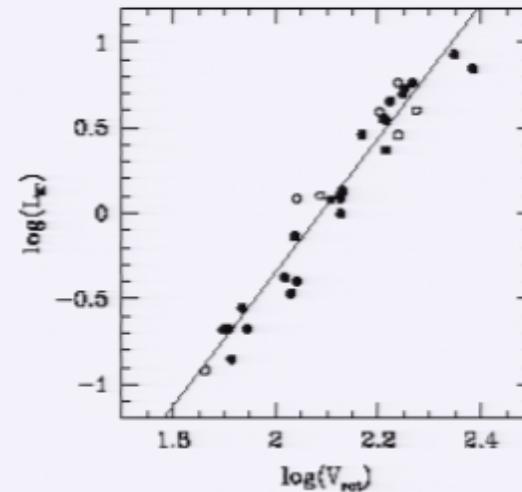
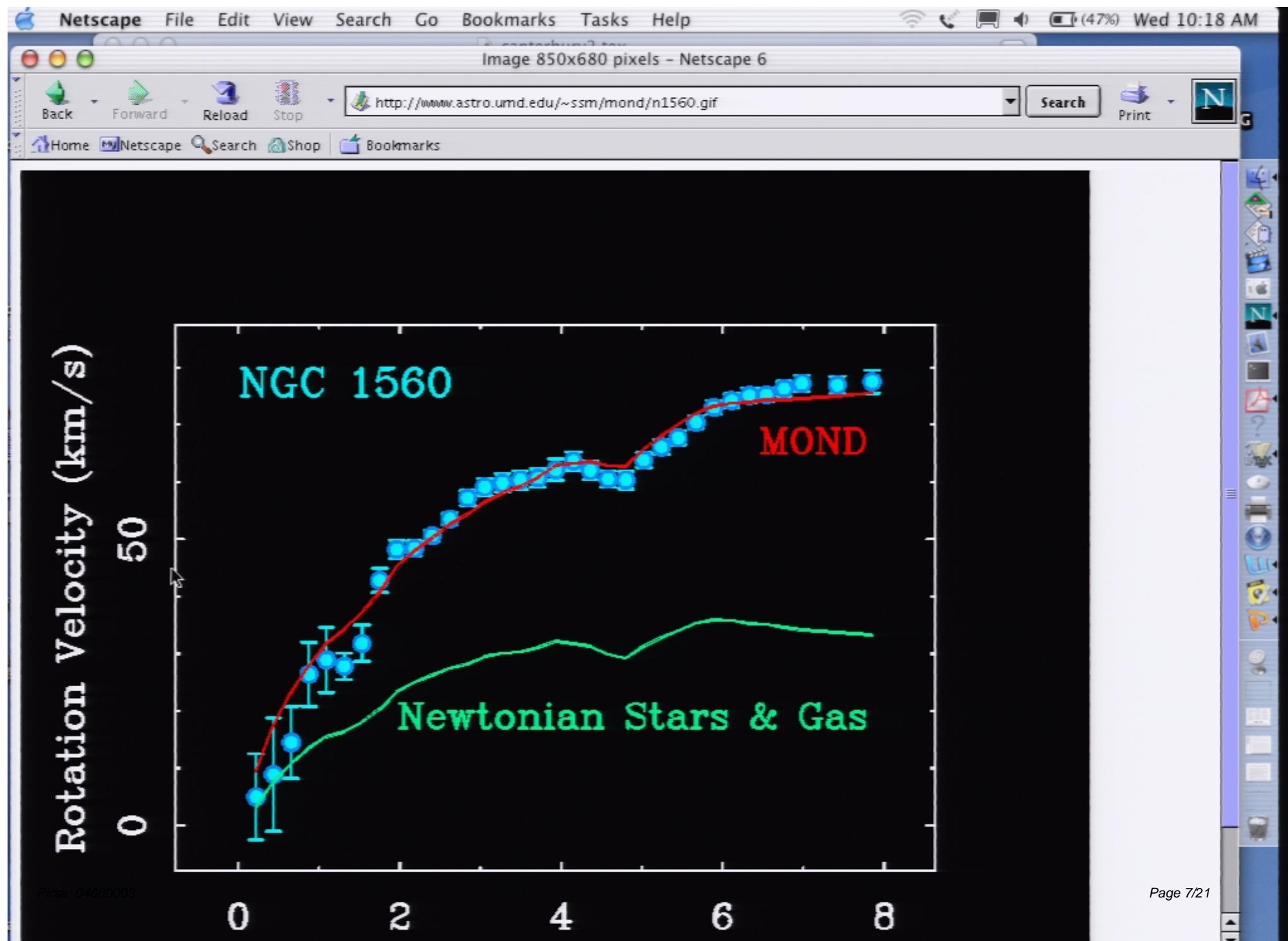
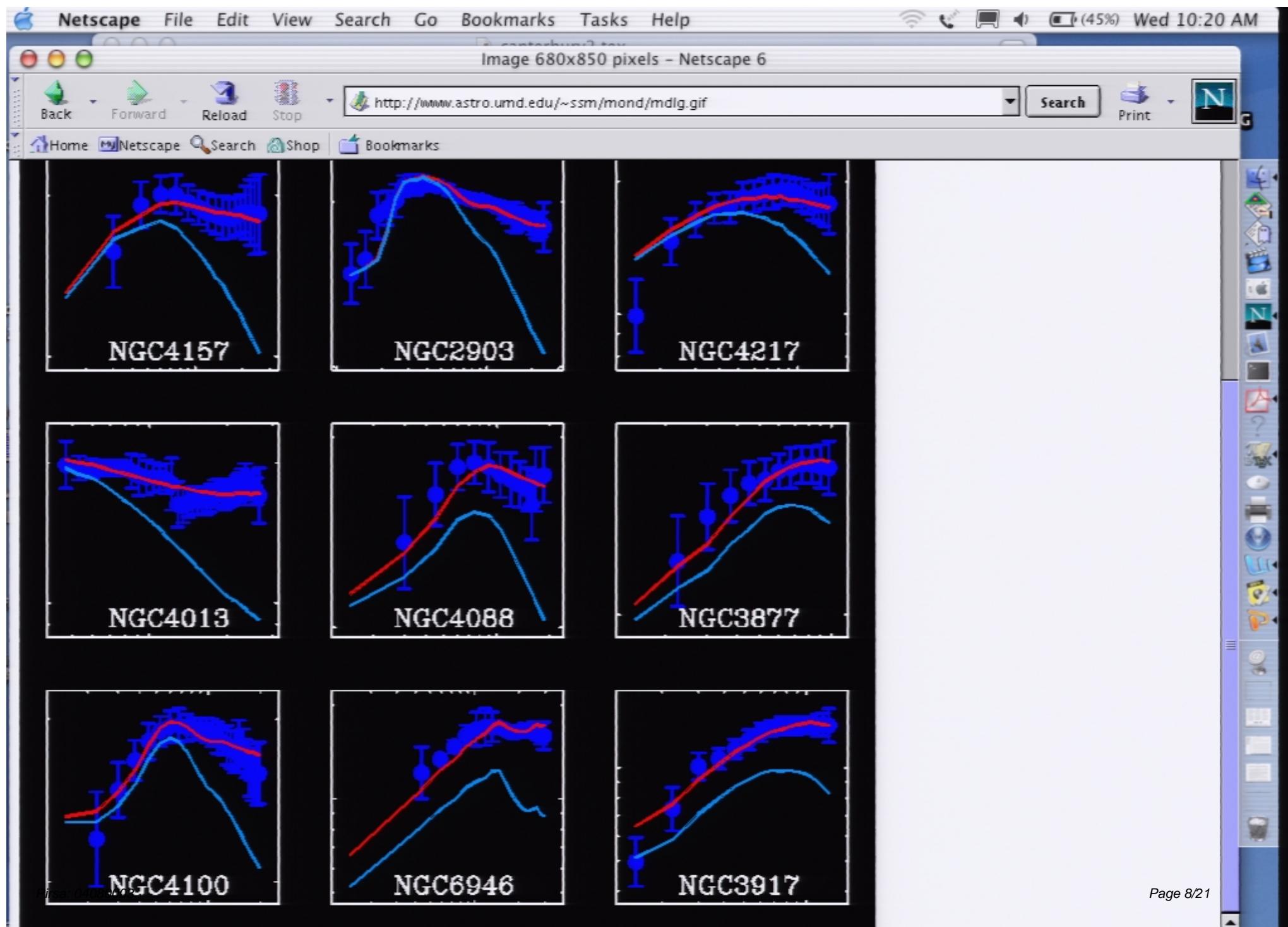
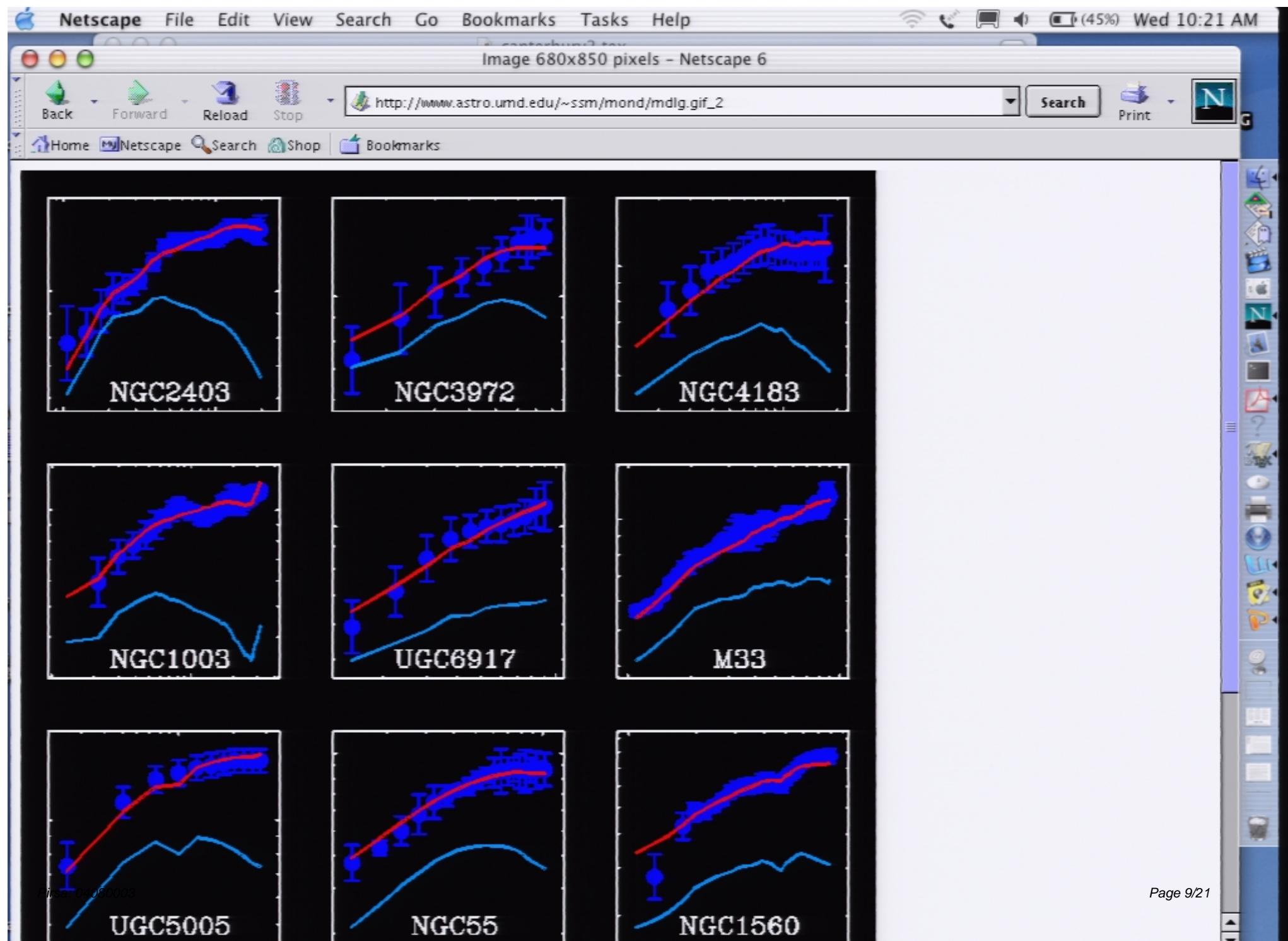


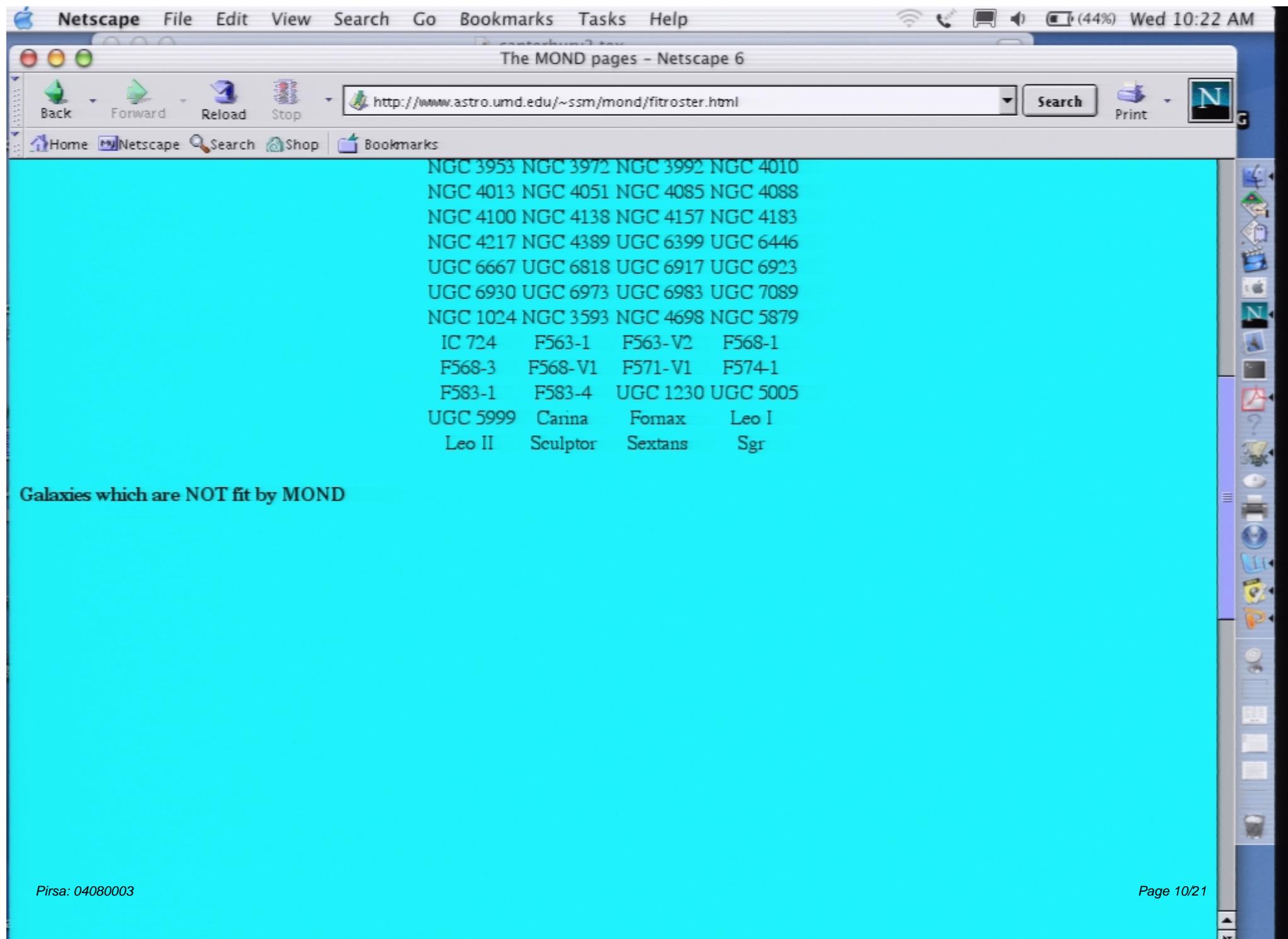
Figure 2: The near-infrared Tully-Fisher relation of Ursa Major spirals ((Sanders & Verheijen 1998)). The rotation velocity is the asymptotically constant value. The velocity is in units of kilometers/second and luminosity in  $10^{10} L_\odot$ . The unshaded points are galaxies with disturbed kinematics. The line is a least-square fit to the data and has a slope of  $3.9 \pm 0.2$ .

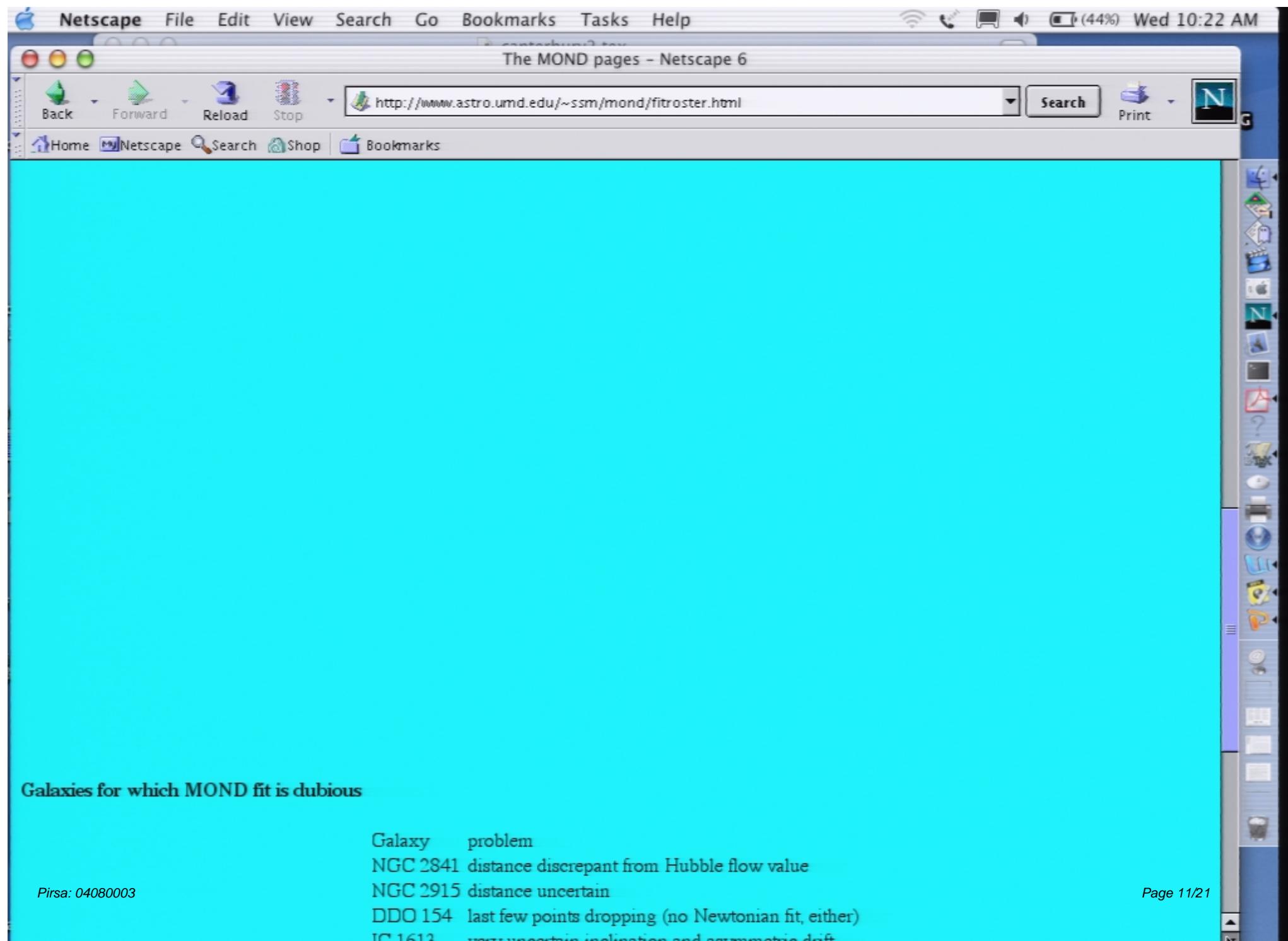
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## Galaxies for which MOND fit is dubious

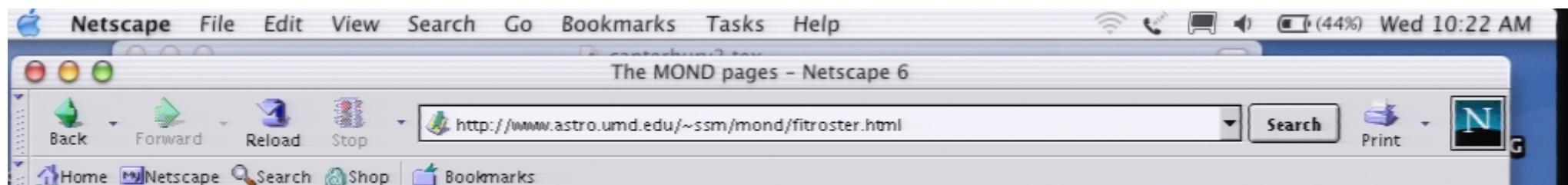
Galaxy problem

NGC 2841 distance discrepant from Hubble flow value

NGC 2915 distance uncertain

DDO 154 last few points dropping (no Newtonian fit, either)

IC 1613 very uncertain inclination and asymmetric drift



## Galaxies for which MOND fit is dubious

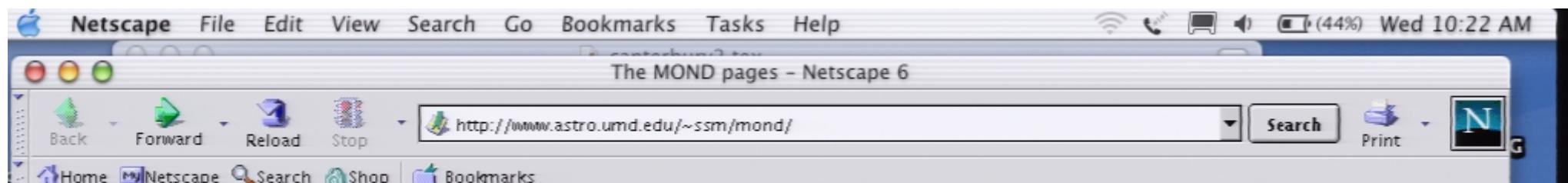
Galaxy problem  
NGC 2841 distance discrepant from Hubble flow value  
NGC 2915 distance uncertain  
DDO 154 last few points dropping (no Newtonian fit, either)  
IC 1613 very uncertain inclination and asymmetric drift  
F565-V2 inclination very uncertain  
UGC 5750 inclination very uncertain  
UGC 6446 distance uncertain  
UGC 6818 interaction?  
UGC 6973 very dusty - does light trace mass?  
Ursa Minor very sensitive to Milky Way parameters  
Draco sensitive to Milky Way parameters

Each of these cases is afflicted by substantial systematic uncertainties. Having the inclination right is very important in a MOND analysis since it enters through  $\sin^4 i$ . Similarly, the physical scale  $a_0$  of MOND requires a proper distance to be known, which may not always be close enough to the Hubble flow value. A particularly interesting case is the dwarf Spheroidal galaxy Ursa Minor. It is very close to the Milky Way which complicates the analysis. The stellar mass-to-light ratio is unacceptably high (~17) if the standard IAU value of the Milky Way rotation velocity (220 km/s) is used. However, the analysis is very sensitive to this. If instead we adopt the more modern estimate of 185 km/s, then the mass-to-light ratio is a much more plausible 4.

Acceptable fits to all these galaxies can be found; the question is whether these are reasonably within the bounds of the uncertainties. Given the nature of astronomical data, I think this is about the right rate of goofs. (You know an astronomer is fudging when there are no goofy data points.)

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I find it remarkable that in **no** case is the fit way off. This is usually what happens when you make up the wrong force law.



## The MOND pages

### Welcome to the MOND pages

This is my personal forum for discussing aspects of the Modified Dynamics proposed by [Moti Milgrom](#) as a solution to the mass discrepancy problem.

#### Scientific Literature

Extensive list of the [literature](#) concerning MOND, complete with links to the actual papers when available, and the occasional commentary.

[The Basic Issue](#), in brief.

[The Dark Matter Tree](#), showing the empirical roots of the mass discrepancy problem and the many proposed branches of solutions.

[Frequently Asked Questions](#)

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#### Material related to the Dynamical Evidence

##### Comparison of MOND and Dark Matter

Includes a table itemizing various observational tests and how each fares.

[Example of a MOND fit](#) to a rotation curve.

[Lots and lots](#) of fits.

These are plotted log(V)-log(R) for data with velocity errors < 5%.

Points with error bars are the data; red lines are the fits; light blue lines are the Newtonian stars+gas.

[Predictions made by Milgrom in 1983](#) which were subsequently confirmed (in [1998](#))

A [MOND fit](#) to the rotation curve of a low surface brightness galaxy.

##### Mass-to-Light Ratios and Stellar Populations

Remarkably reasonable.

[Roster of galaxies](#) which have been used to test MOND:

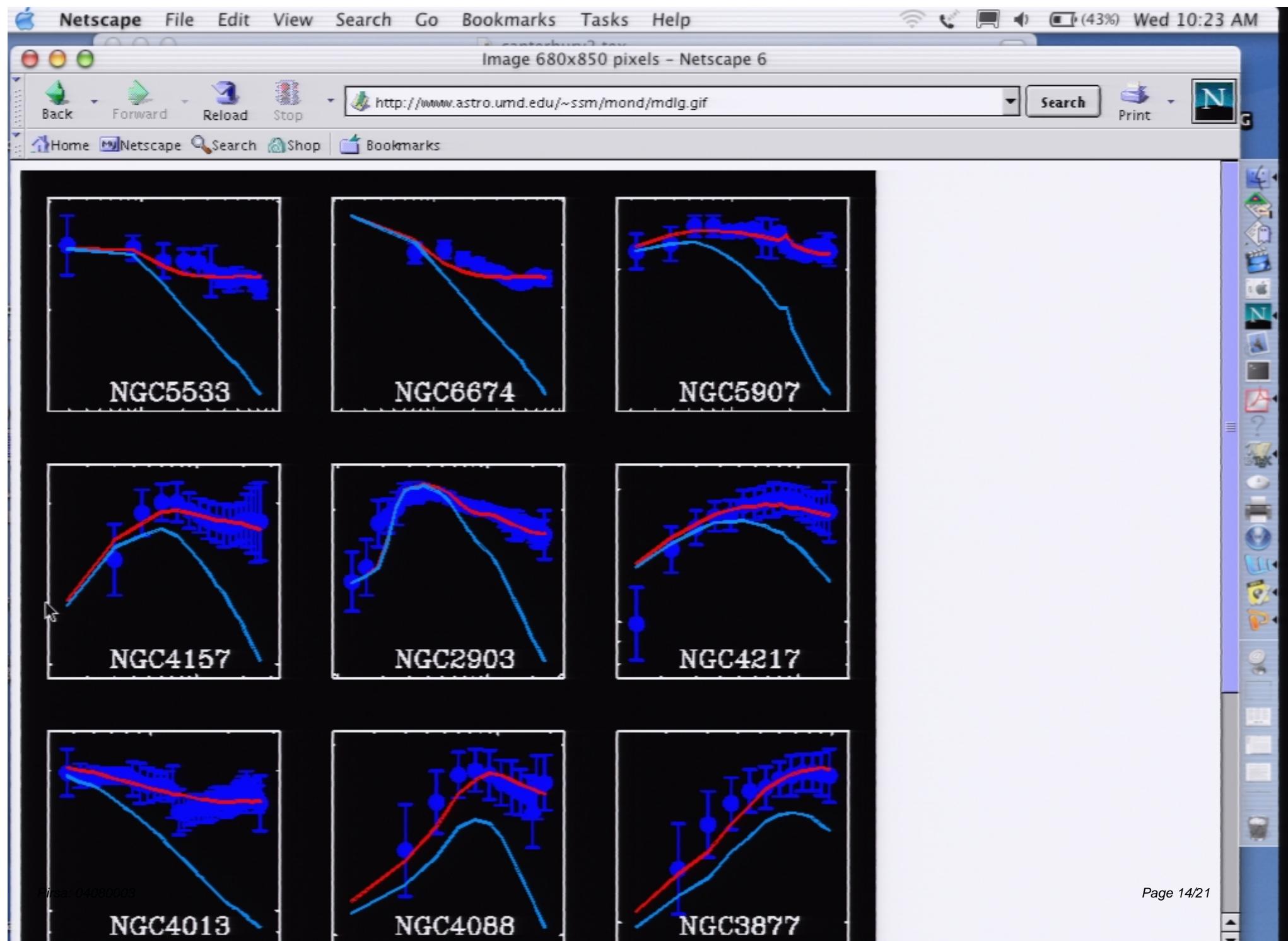
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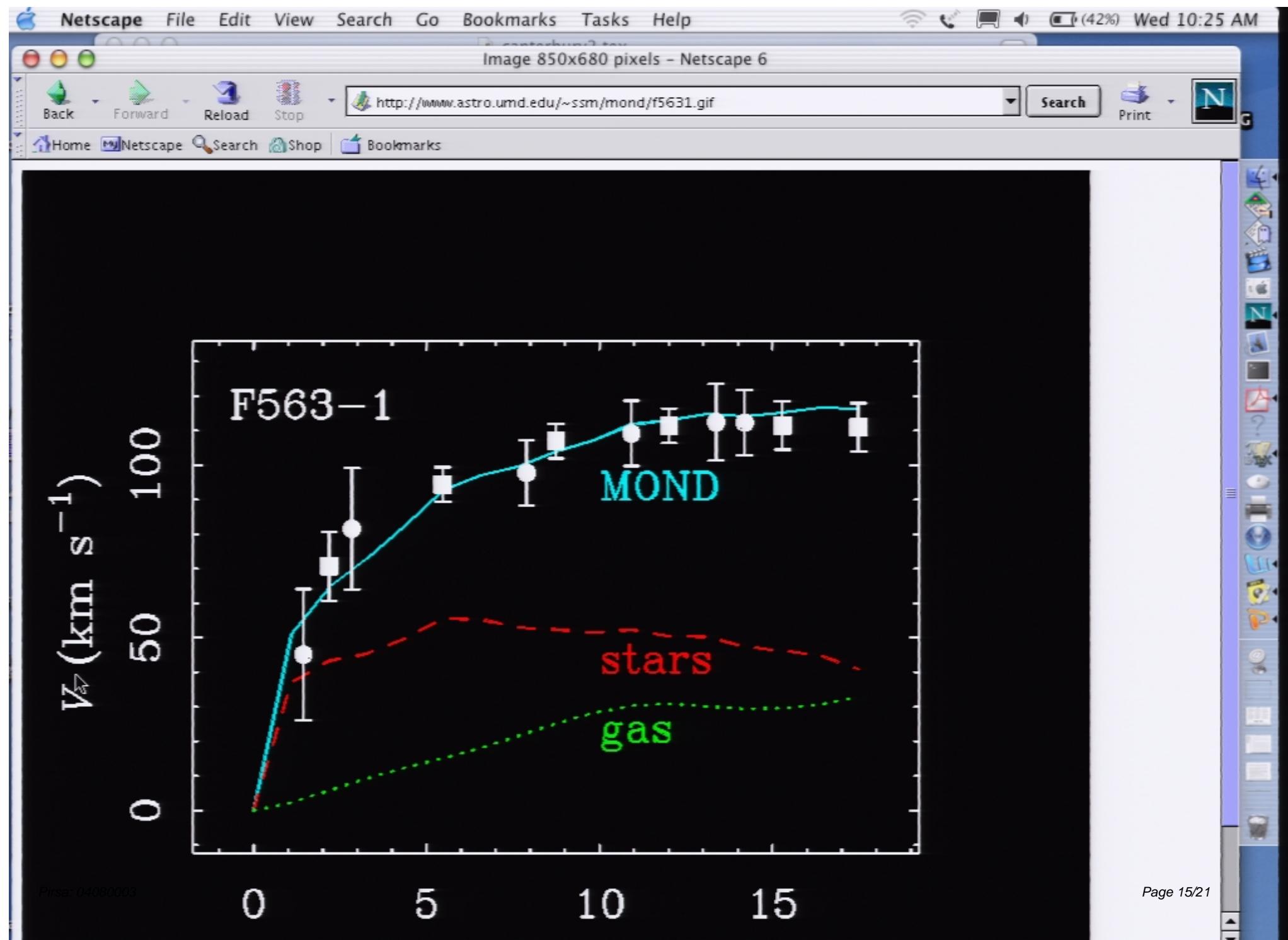
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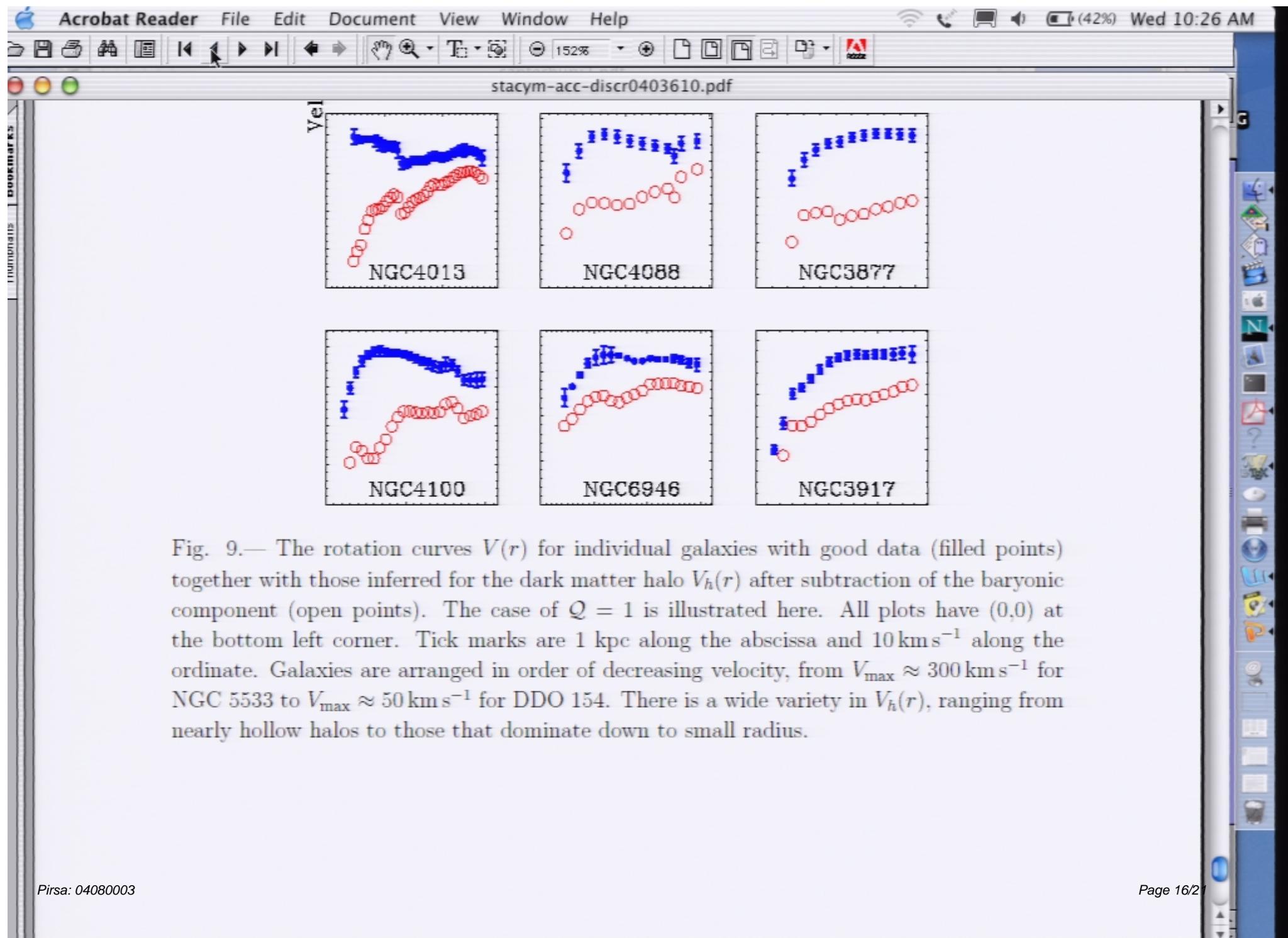
#### N-body computations

Modelers beware: implementing MOND is not a one line change to standard particle-pushing codes. [Chris Mihos explains why](#) (The inertial modification is inherently nonlocal.)

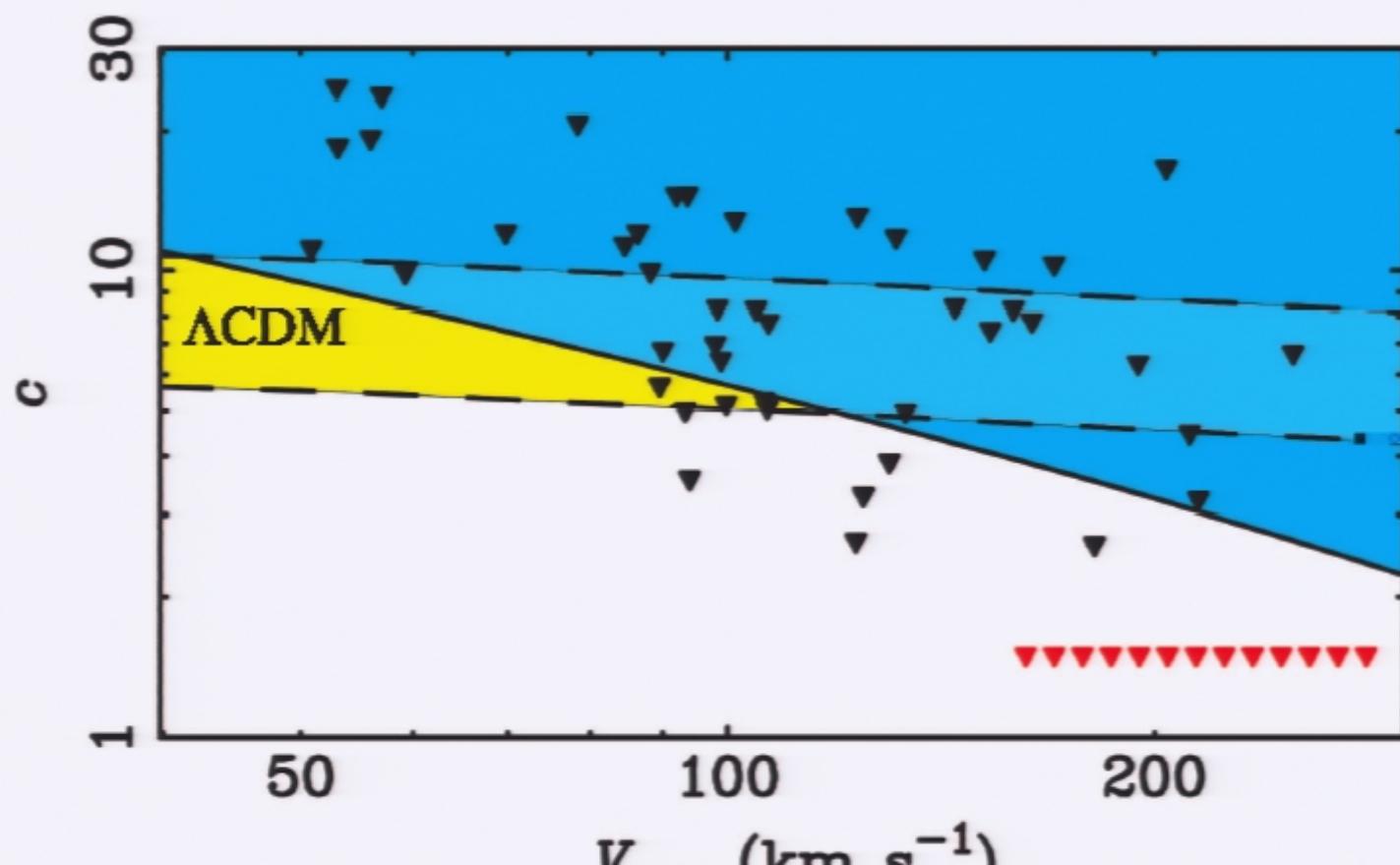
Other numerical approaches are necessary. The only good example of which I am aware is in [Brada's thesis](#).



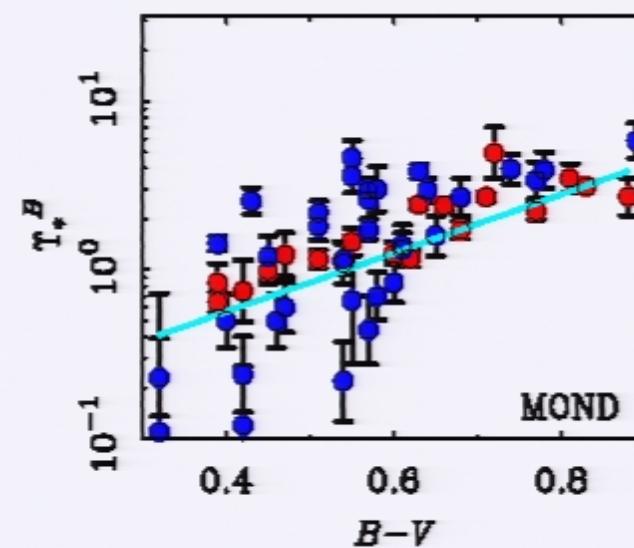
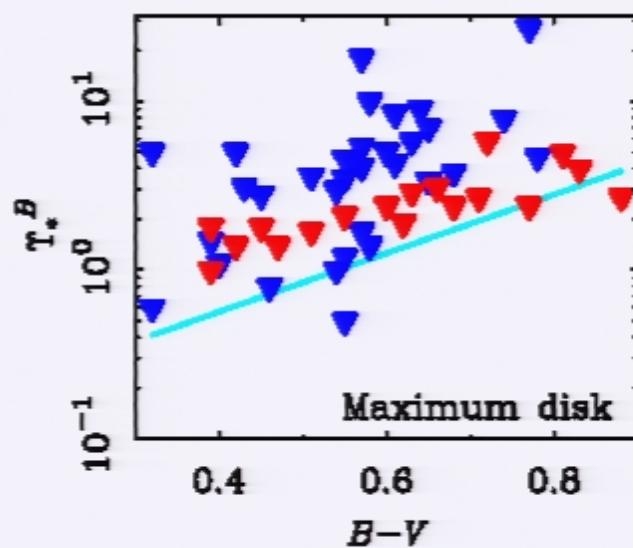




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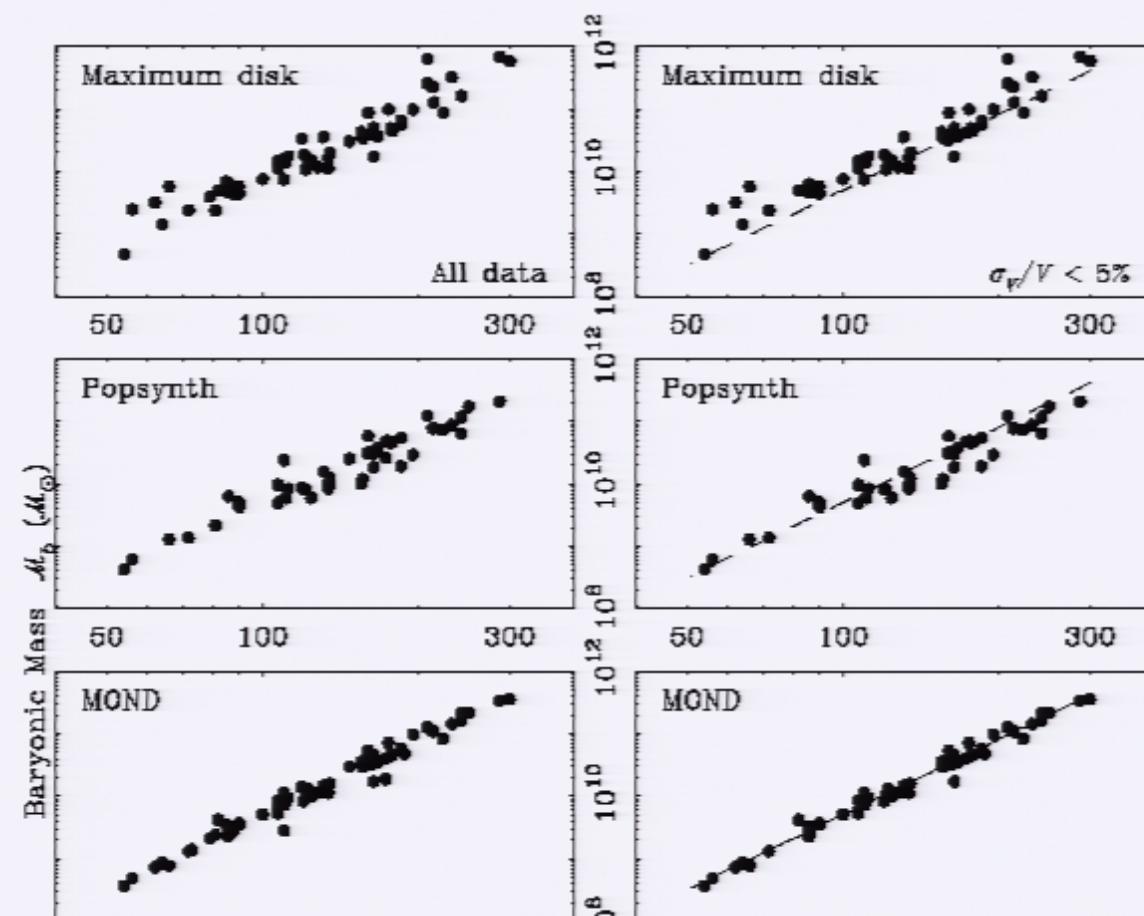


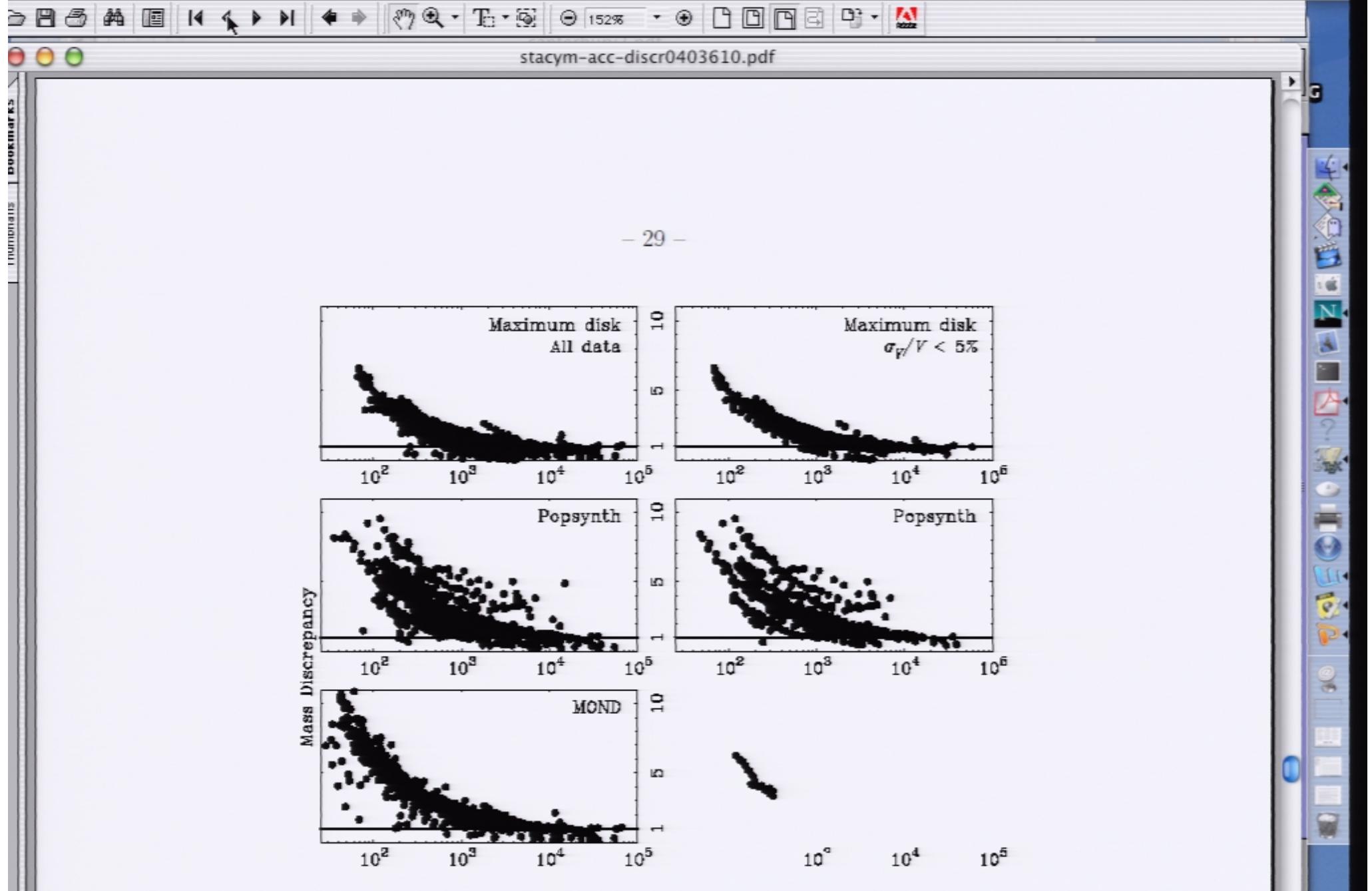
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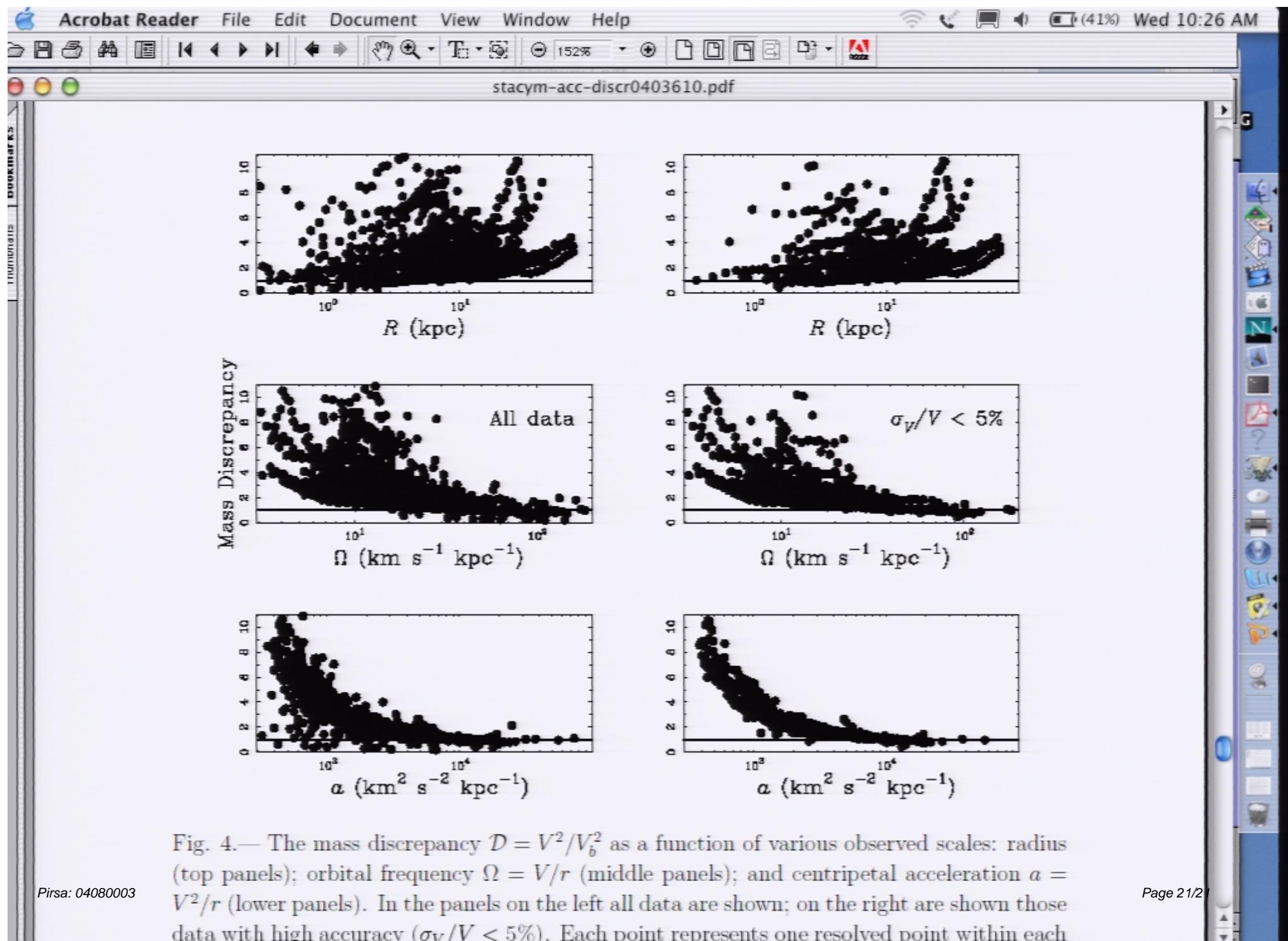


Fig. 4.— The mass discrepancy  $\mathcal{D} = V^2/V_b^2$  as a function of various observed scales: radius (top panels); orbital frequency  $\Omega = V/r$  (middle panels); and centripetal acceleration  $a = V^2/r$  (lower panels). In the panels on the left all data are shown; on the right are shown those data with high accuracy ( $\sigma_V/V < 5\%$ ). Each point represents one resolved point within each