1. How do we parameterize ram pressure stripping for a SAM?

Nothing is absolutely perfect, but I think that finding the radius of equality between the integrated ram pressure and the maximum restoring force along the line of sight of the wind times the sound crossing time out to the virial radius is very close. Then, how you want to model "continuous" stripping is still a bit of a question.

2. Galaxy Models

I have used two galaxy models. I had to change some of the values from what Andrew sent me so that the gas would actually be stripped to within a reasonable radius.

Table 1: Galaxy Parameters

Variable	Galaxy 1	Galaxy 2
R_{vir}	74 kpc	40.3 kpc
v_{max}	55.8 km/s	43.6 km/s
r_{DM}	3.7742 kpc	2.6008 kpc
ρ_{DM}	1.272e-24 g cm^{-3}	1.63e-24 g cm^{-3}
M_{gas}	1.073715e7 $M_\odot$	1.073715e7 $M_\odot$
$r_{scale,halo}$	1.86 kpc	.74366 kpc
ρ_{halo}	1.272e-25 g cm^{-3}	1.63e-25 g cm^{-3}
$M_{stellardisk}$	1.073715e6 $M_\odot$	3.238019e6 $M_\odot$
R_{scale}	1.86 kpc	.74366 kpc
z_{scale}	.37205 kpc	.148732 kpc
M_{bulge}	2.774e6 $M_\odot$	3.7288e6 $M_\odot$
r_{bulge}	.44057 kpc	.33157 kpc

3. Galaxy 1

I have run more wind models on Galaxy 1, so will consider that first. When I consider the total mass in a ring or the sound crossing time (t_{sound}), the values are the total across all the gas associated with the galaxy (with a tracer fraction more than 0.33, although a selection of 0.6 or 0.85 does not make much difference), which in this case begins as a sphere with a radius of about 55 kpc (it was initially set using a density criteria).

3.1. Instantaneous Wind Comparisons

I can compare instantaneous wind values, measured next to the disk in the disk plane, to the properties of the disk in static surroundings. The nearly horizontal lines are the unmolested disk, although you can see that the disk is not completely stable. The thicker lines are the ram pressure of the wind (ρv^2). The strange color-coding is a rough match to what radius should **survive**. The outer color is from the instantaneous wind comparison (Figure 2), and the inner color is from the integrated wind comparison (Figure 3).

3.2. Integrated Wind Comparisons

Since the instantaneous wind comparisons don't account for the total ram pressure experienced, we can also look at the integral of the ram pressure.

3.3. Gas Stripping Profiles

So now we have our predictions, and can see how they stand up to how much gas is actually stripped. We go through this wind profile by wind profile. The left panel of each set of figures has one that is entirely from the stripped galaxy. The left panel shows the gas mass in narrow (0.5 kpc) cylindrical rings that end at the radius specified at the edge of the plot. The rings are 60 kpc above and below the disk plane, but only include gas that has a tracer fraction of 0.33–must have 33% of the gas in the cell from the original galaxy. The traced region is a sphere about 55 kpc in radius, so a bit smaller than the virial radius (about 75 kpc). I think these panels are good evidence that looking at the galaxy as rings of distance from the galaxy center and perpendicular to the wind direction is the way to go (rather than something like spherical shells).

The right panels show the gas mass of the stripped galaxy (thick lines) within cylinders with a height of 60 kpc and a radius of either 30 kpc or 50 kpc with a series of tracer fraction cuts. The dashed line is 33%, the solid line is 66% and the dot-dashed line is 85%. These lines are over plotted on lines of gas mass within a cylinder of height 60 kpc and radius as labeled on the figure. The colors are the same as those in Figure 3. I also have a few thin brown lines plotted to start thinking about continuous stripping. These are the amount of wind mass that has crossed the plane of the disk in a circle with a radius the same as predicted in Figure 3. I start the calculation at a few times: at the beginning of the simulation, at the time of maximum RP (solid vertical line), and the time of maximum RP plus the sound crossing time from the disk plane to 60 kpc above the disk (dashed vertical line).

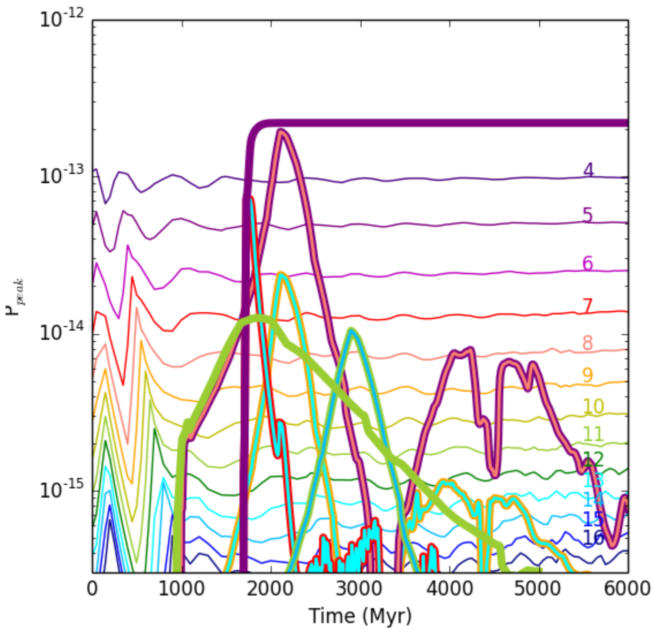

Fig. 1.— One possible comparison, loosely related to the comparison made in More & Burkert (2000). Compare the peak pressure in the galaxy along a column in the wind direction (here the z-direction) because the pressure $\sim$ the gravitational restoring force to the ram pressure. I have lines for the peak pressure at several radii in the galaxy. As I will show, this comparison predicts much more gas will be removed than is actually found in the simulation.

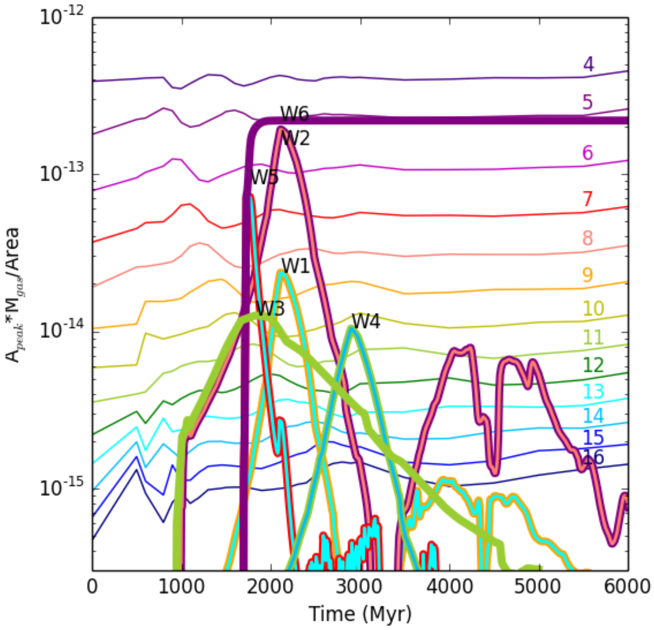

Fig. 2.— Another possible comparison, loosely related to McCarthy et al. (2008). Compare the ram pressure to the restoring force, calculated as the magnitude of the peak gravitational acceleration times the column density of gas in the galaxy at that radius. I have made this more generous using the magnitude of the total acceleration rather than simply in the z-direction. The idea is that all the gas has to pass through this "max restoring acceleration" point, so use that. As above, I have lines for the restoring force at several radii in the galaxy. Also as above, this doesn't seem to work, and does not include any accounting for time or total RP experienced.

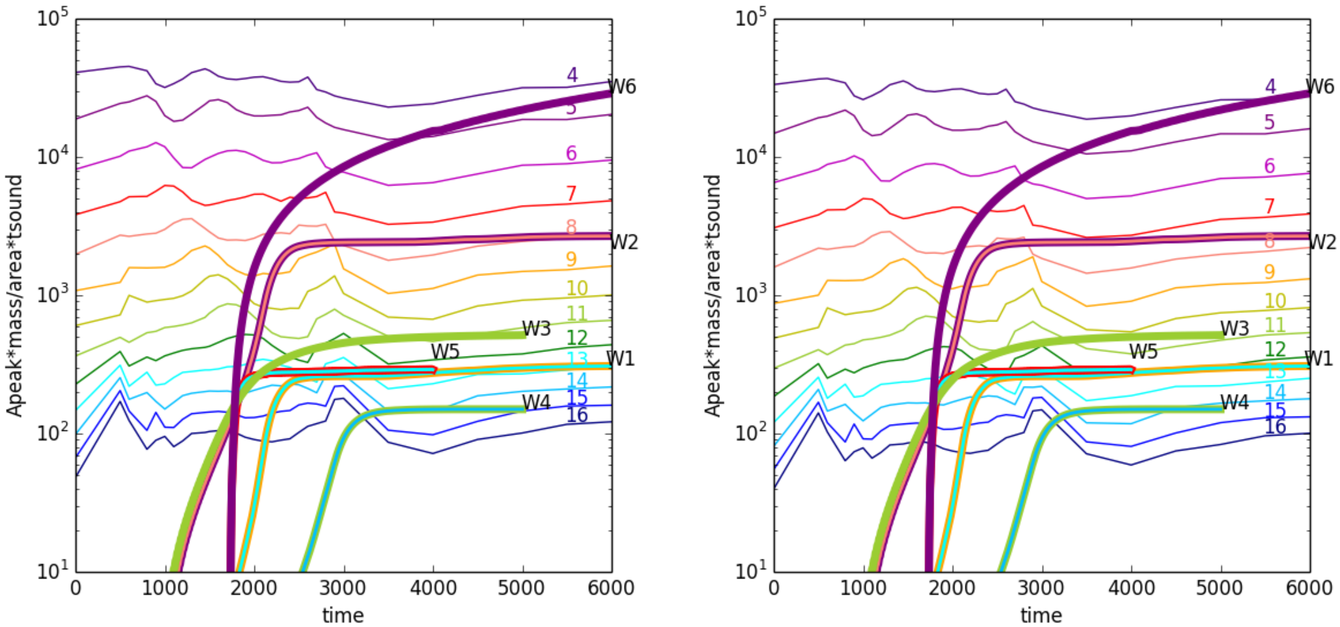

Fig. 3.— Comparing the integral of the ram pressure to the restoring force times the sound crossing time. **Left Panel:** As before, the peak gravitational acceleration is the magnitude of the total acceleration. **Right Panel:** The peak gravitational acceleration is the magnitude of the acceleration *only in the z-direction, aka the wind direction.* In both panels the sound crossing time is calculated directly from the code as the sum of the time it takes to cross a cell ($\Delta z \times c_{sound}$) x Area of that cell ($\Delta y \Delta x$), divided by the area of the ring. $(\sum_i \Delta z_i c_{sound,i} \Delta x_i \Delta y_i)/A_{ring}$

As you will see, generally the "predicted" amount of stripping is larger than the observed amount of stripping. I see two possibilities for this: 1) It is the sound crossing time from virial radius to virial radius that counts, so all of the horizontal-ish lines should shift up a bit (although not much because we are talking 60 kpc instead of 75 kpc radius). This gives us a nice way to choose what the sound crossing time actually should be, because choosing a random radius for the calculation doesn't seem helpful, and 2) it isn't the total integrated ram pressure, but the total integrated ram pressure up to the time of peak RP.

3.3.1. Wind 1

Our first wind is predicted to strip gas to either 8 kpc (instantaneous, Figure 2), 12-13 kpc (integrated, Figure 3), or 15 kpc (integrated to t_{maxRP} Figure 3). Using just the acceleration in the z-direction (right panel of Figure 3), the prediction is 15 kpc only integrated to t_{maxRP}.

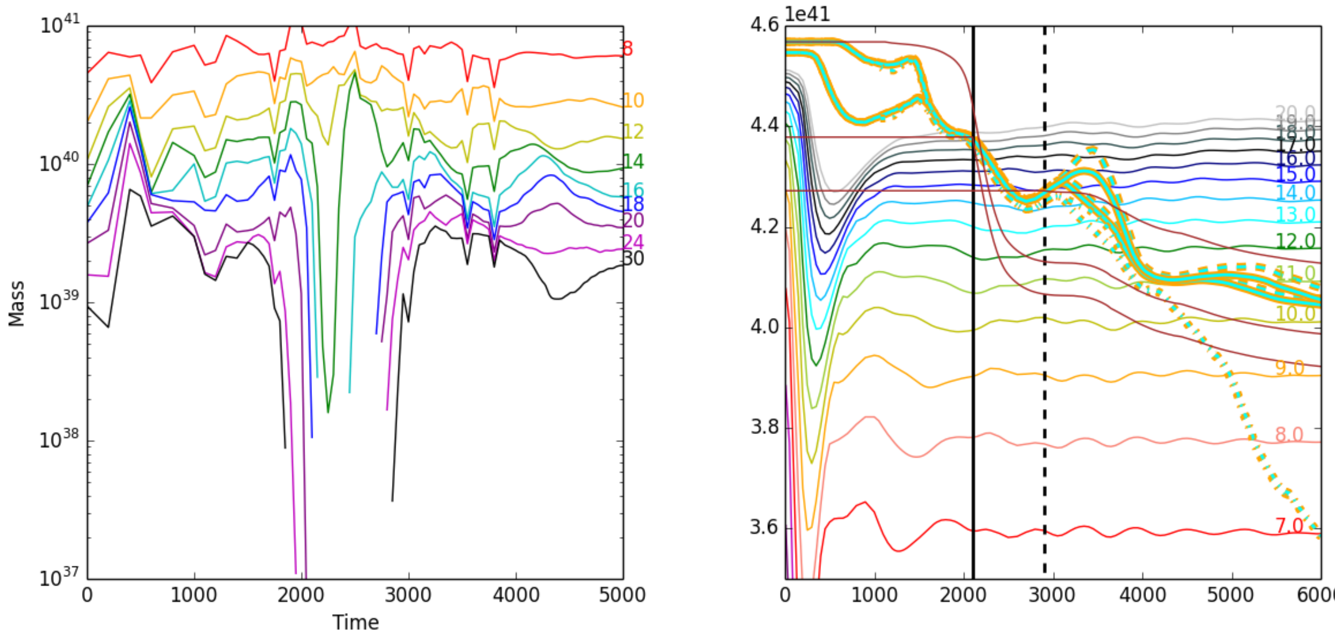

Fig. 4.— Wind 1: **Left Panel:** When we look at what happens to the gas in a ring with a width of 0.5 kpc that is oriented in the wind direction, we see that the integrated profile seems more right than the instantaneous. However, fallback and hydro effects make this a bit difficult to interpret. Also, this includes gas that might be unbound but is within 60 kpc of the disk plane, so might include gas stripped from an inner radius that moves to a larger radius in the flared tail. The color scheme is different here. **Right Panel:** I would say that ram pressure stripping takes us to the first minimum, just before the dashed vertical line. That looks more like 14 kpc, not 13 and certainly not 12 kpc. This agrees pretty well with what we see in the left panel, and really isn't too far from our prediction using the integrated ram pressure, and is even better when we only integrate up to t_{maxRP}. Anybody's guess is as good as mine on what to do after the minimum. Also, note we are looking at quite long timescales (6 Gyr).

3.3.2. Wind 2

The second wind has the same shape as the first, but is quite a bit stronger. I did this by changing the density profile of the MW halo, so the orbit (distance and velocity) is unchanged. It is predicted to strip gas to either 5 kpc (instantaneous, Figure 2), ∼8 kpc (integrated, Figure 3), or 9 kpc (integrated to t_{maxRP} Figure 3). Using just the acceleration in the z-direction (right panel of Figure 3), the prediction is 9 kpc only integrated to t_{maxRP}.

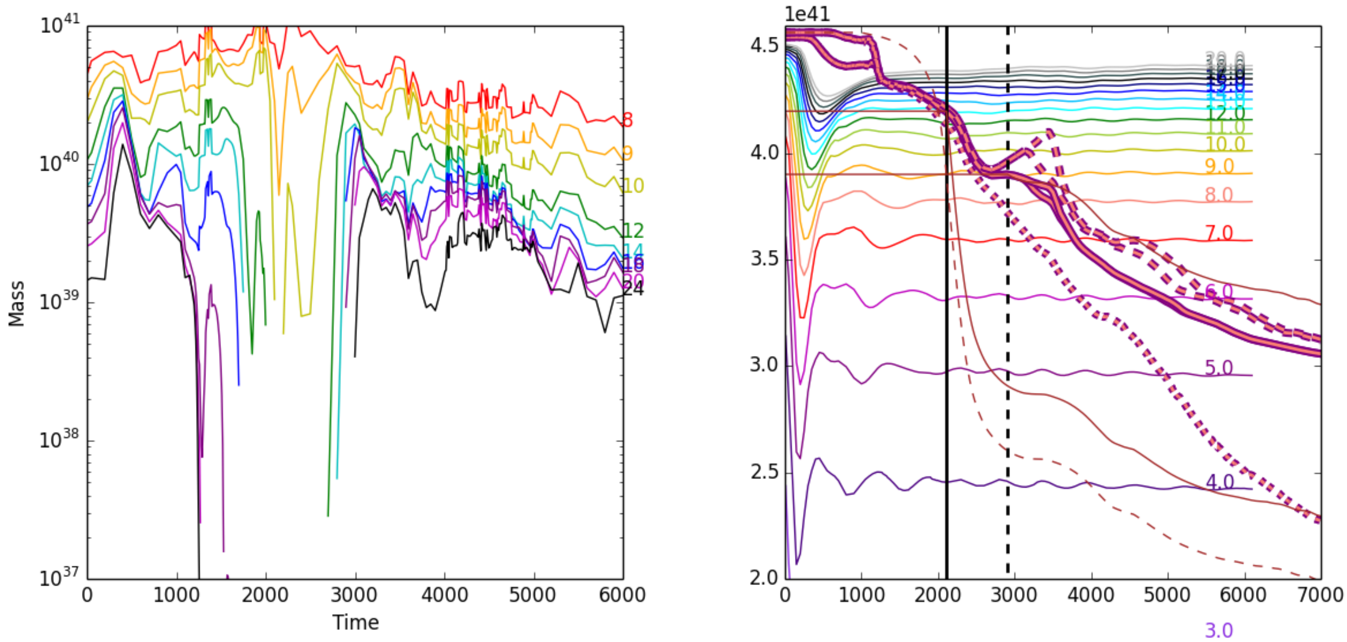

Fig. 5.— Wind 2: **Left Panel:** This one is actually the gas mass in a ring that is 30 kpc above and below the disk, but the idea is the same. Here you see that 8 kpc is basically fine, 9 kpc may or may not be stripped, and 10 kpc is definitely stripped for a bit. **Right Panel:** As in Figure 4, this panel agrees nicely with the left panel and has a bit less stripping than predicted by Figure 3, although it agrees pretty well with the integrated RP up to t_{maxRP}.

3.3.3. Wind 3

The third wind has a broader profile than the first two, which results in a lower peak RP but a larger integrated RP than Wind 1. It is predicted to strip gas to either 10 kpc (instantaneous, Figure 2), ∼11-12 kpc (integrated, Figure 3), or 14 kpc (integrated to t_{maxRP} Figure 3). Using just the acceleration in the z-direction (right panel of Figure 3), the prediction is stripped to just under 14 kpc only integrated to t_{maxRP}.

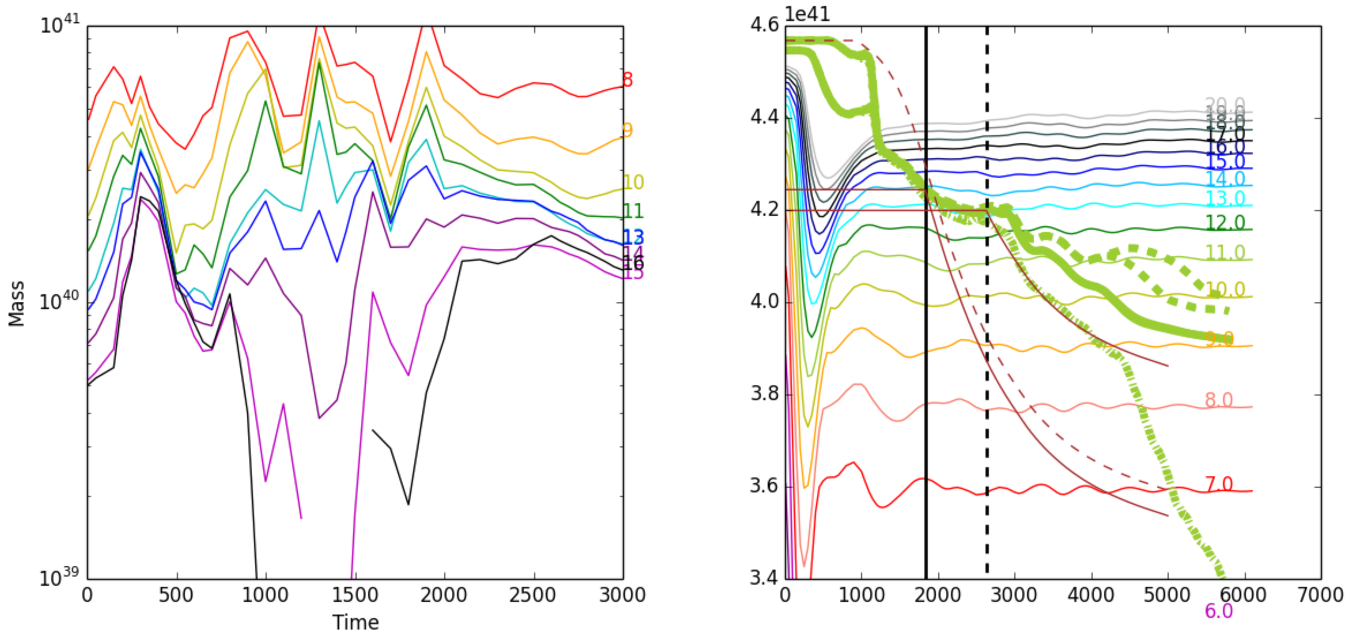

Fig. 6.— Wind 3: **Left Panel:** Here you can debate whether the 14 kpc ring is stripped, but it is clear that the 15 kpc ring is stripped for a bit. **Right Panel:** This panel actually shows more stripping than the left panel. It still has a bit less stripping than predicted by Figure 3, and more stripping than predicted by the integrated RP up to t_{maxRP}.

3.3.4. Wind 4

This is the weakest wind of the bunch, but it is still predicted to strip gas to either 10 kpc (instantaneous, Figure 2), ∼14-15 kpc (integrated, Figure 3), or 16-17 kpc (integrated to t_{maxRP} Figure 3). Using just the acceleration in the z-direction (right panel of Figure 3), the prediction is 16-17 kpc only integrated to t_{maxRP}.

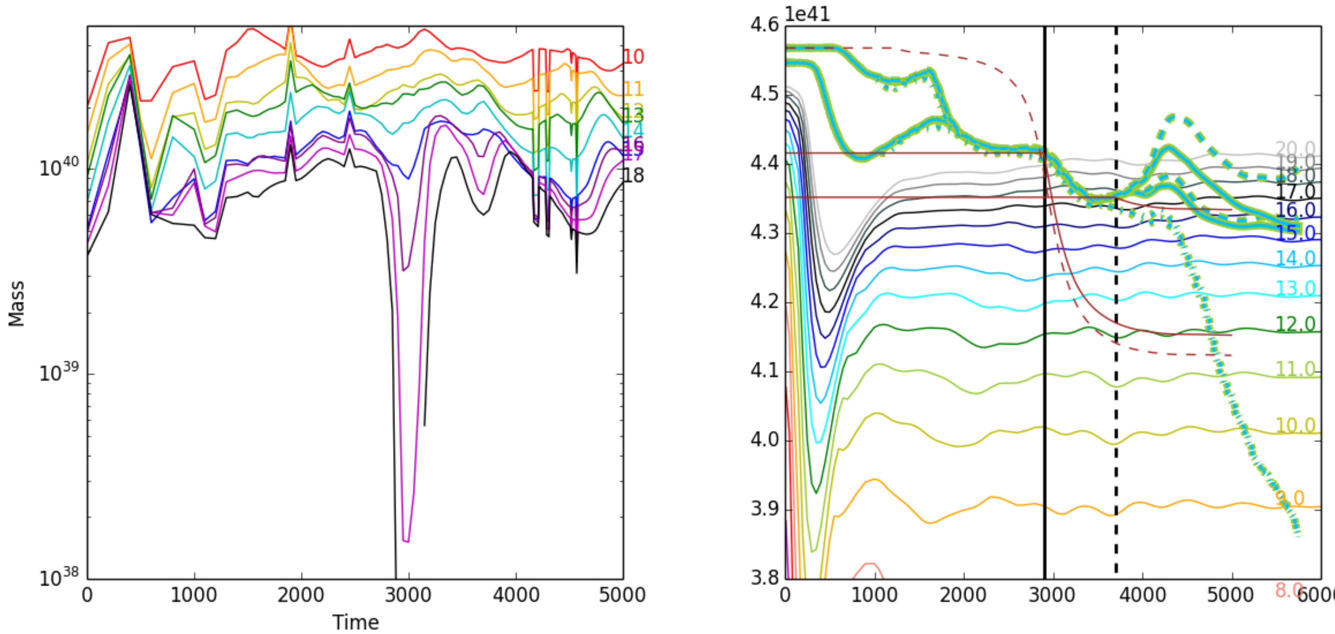

Fig. 7.— Wind 4: **Left Panel:** Here you can debate whether the 16 kpc ring is stripped, but I would definitely say the 17 kpc ring is stripped for a bit. **Right Panel:** This panel agrees pretty well with the left panel. It has less stripping than predicted by Figure 3, but agrees pretty well with the prediction from the integrated RP up to t_{maxRP}.

3.3.5. Wind 5

This is a quite unrealistic wind because I have it suddenly slamming into the galaxy without the orbital info that I used for the first 4 winds. Since it is a sudden shock rather than a more slowly increasing wind, perhaps the integrated RP vs a value that involves the sounds crossing time is not appropriate for this one. It is predicted to strip gas to either just over 7 kpc (instantaneous, Figure 2), ∼12-13 kpc (integrated, Figure 3), or 15 kpc (integrated to t_{maxRP} Figure 3).

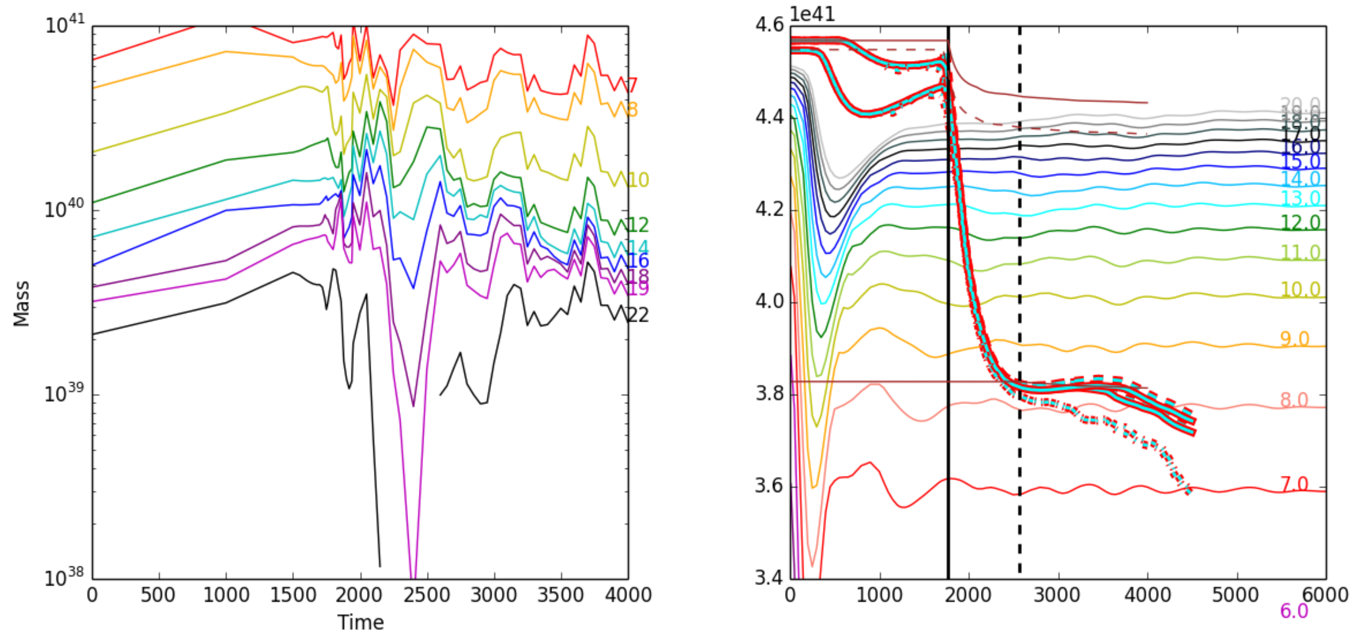

Fig. 8.— Wind 5: **Left Panel:** Here you can debate whether the 18 kpc ring is stripped, but I would definitely say the 19 kpc ring is stripped for a bit. Unlike the first 4 winds, this looks like less stripping than any of the predictions. **Right Panel:** This panel TOTALLY DISAGREES with the left panel. It has nearly as much stripping as predicted by Figure 2 instead of either of the integrated methods. Perhaps an instantaneous shock is better described by comparing the instantaneous RP to the restoring force? There is the pesky problem that suddenly my nice rings description doesn't seem to work, but we can still use the RP profile to make a prediction.

3.3.6. Wind 6

This is another unrealistic wind because I have it suddenly slamming into the galaxy without the orbital info that I used for the first 4 winds. Here I don't have a quick instantaneous wind, instead I keep it constant at the peak. As in Wind 5, since it is a sudden shock rather than a more slowly increasing wind, perhaps the integrated RP vs a value that involves the sounds crossing time is not appropriate for this one. It is predicted to strip gas to 5 kpc (instantaneous, Figure 2), ~5 kpc, or possibly just all gas (integrated, Figure 3), or 9 kpc (integrated to t_{maxRP} Figure 3).

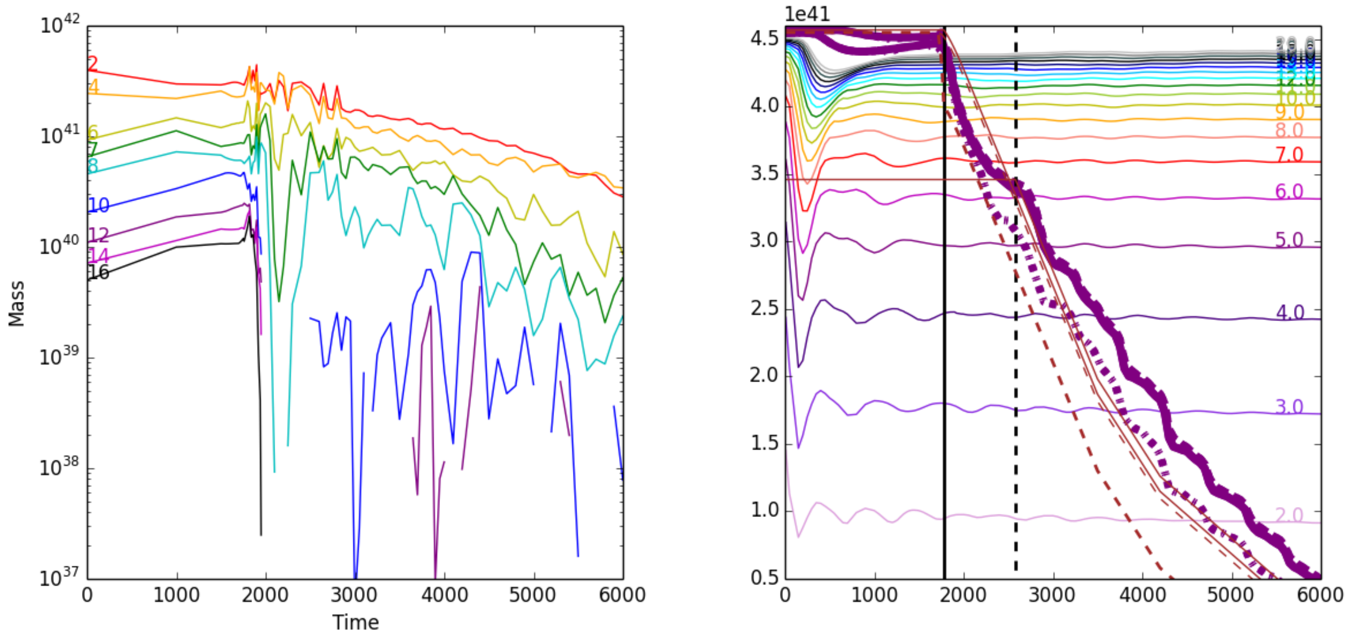

Fig. 9.— Wind 6: **Left Panel:** Here you can debate whether the 7 kpc ring is stripped, but the 8 kpc ring is clearly removed for a bit. This looks a bit between the two types of predictions. **Right Panel:** This panel shows pretty strong stripping throughout, but I would say that RP goes to 6 kpc. It has nearly as much stripping as predicted by Figure 2. Even though one might like the continuous stripping to look like the integrated RP, in other words, track it over time, the stripping is faster than predicted by the integrated RP. I also fiddled with the "continuous stripping" calculation on this one–instead of just leaving the radius constant when I calculate how much wind mass has passed the disk, I changed it at a few points to match the radius the thick line was crossing in the unperturbed disk. At 3.5 Gyr I changed the radius from 5 kpc to 4 kpc, and at 4.2 Gyr I changed it to 3 kpc.

4. Galaxy 2

I ran a couple winds with another galaxy model to make sure that the results didn't vary when I changed galaxies. When I consider the total mass in a ring or the sound crossing time (t_{sound}), the values are the total across all the gas associated with the galaxy (with a tracer fraction more than 0.33, although a selection of 0.6 or 0.85 does not make much difference), which in this case begins as a sphere with a radius of about 40 kpc. Unlike when I ran Galaxy 1, by now I realized that t_{sound} needed an explanation, so I just used a radius criteria when setting the original tracer fraction.

4.1. Instantaneous Wind Comparisons

I can compare instantaneous wind values, measured next to the disk in the disk plane, to the properties of the disk in static surroundings. The nearly horizontal lines are the unmolested disk, although you can see that the disk is not completely stable. The thicker lines are the ram pressure of the wind (ρv^2). The strange color-coding is a rough match to what radius should **survive**. The outer color is from the instantaneous wind comparison (Figure 2), and the inner color is from the integrated wind comparison (Figure 3).

4.2. Integrated Wind Comparisons

Since the instantaneous wind comparisons don't account for the total ram pressure experienced, we again also look at the integral of the ram pressure.

4.3. Gas Stripping Profiles

These are as described above, just with Galaxy 2! To reiterate: The left panel of each set of figures has one that is entirely from the stripped galaxy. The left panel shows the gas mass in narrow (0.5 kpc) cylindrical rings that end at the radius specified at the edge of the plot. The rings are 60 kpc above and below the disk plane, but only include gas that has a tracer fraction of 0.33–**for Galaxy 2 this was set at 40 kpc radius to start**.

The right panels show the gas mass of the stripped galaxy (thick lines) within cylinders with a height of 60 kpc and a radius of either 30 kpc or 50 kpc with a series of tracer fraction cuts. The dashed line is 33%, the solid line is 66% and the dot-dashed line is 85%. These lines are over plotted on lines of gas mass within a cylinder of height 60 kpc and radius as labeled on the figure. The colors are the same as those in Figure 11. I also have a few thin brown lines plotted to start thinking about continuous stripping. These are the amount of wind mass that has crossed the plane of the disk in a circle with a radius the same as predicted in Figure 3. I start the calculation at a few times: at the beginning of the simulation, at the time of maximum RP (solid vertical line), and the time of maximum RP plus the sound crossing time from the disk plane to 60 kpc above the disk (dashed vertical line).

As you will see, generally the "predicted" amount of stripping using the "total" integrated amount is larger than the observed amount of stripping. Unlike before, I set the tracer fraction to 1 inside the virial radius, so there is not much room to maneuver there–although since this galaxy isn't totally stable we might have some wiggle room. This leads me back

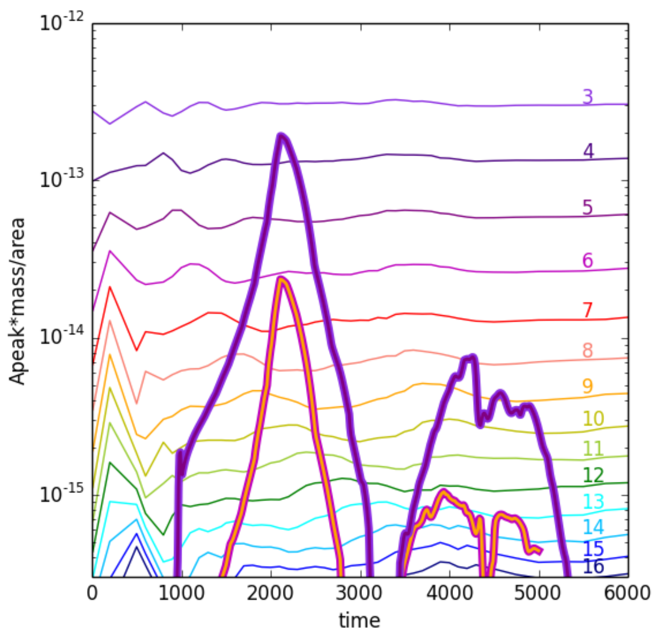

Fig. 10.— As in Figure 2. Compare the ram pressure to the restoring force, calculated as the magnitude of the peak gravitational acceleration times the column density of gas in the galaxy at that radius. I have made this more generous using the magnitude of the total acceleration rather than simply in the z-direction. **This one does not even include a fudge for the halo gas. This should be a small correction, but makes these values slightly low.** The idea is that all the gas has to pass through this ”max restoring acceleration” point, so use that. As above, I have lines for the restoring force at several radii in the galaxy. Also as above, this doesn’t seem to work, and does not include any accounting for time or total RP experienced.

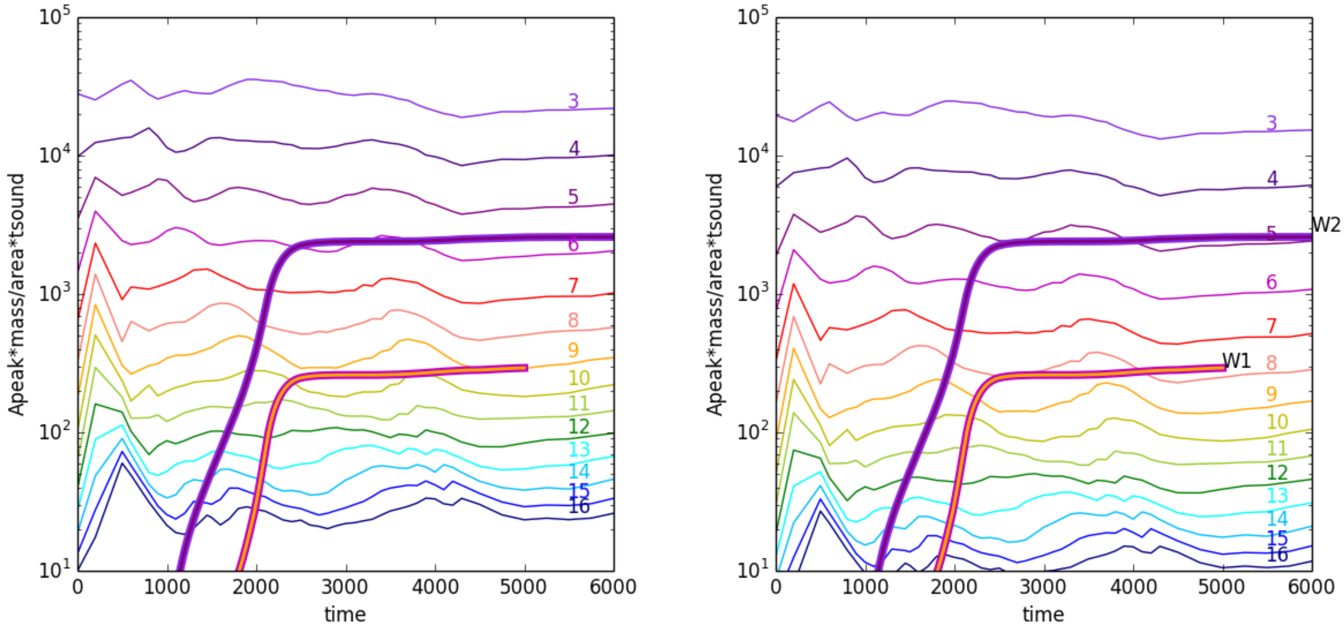

Fig. 11.— Comparing the integral of the ram pressure to the restoring force times the sound crossing time. **Left Panel:** As before, the peak gravitational acceleration is the magnitude of the total acceleration. **Right Panel:** The peak gravitational acceleration is the magnitude of the acceleration *only in the z-direction, aka the wind direction.* In both panels the sound crossing time is calculated directly from the code as the sum of the time it takes to cross a cell ($\Delta z \times c_{sound}$) x Area of that cell ($\Delta y \Delta x$), divided by the area of the ring. $(\sum_i \Delta z_i c_{sound,i} \Delta x_i \Delta y_i)/A_{ring}$

to: it isn't the total integrated ram pressure, but the total integrated ram pressure up to the time of peak RP. Of course, for Galaxy 2 we see that that prediction tends to be a bit low!

4.3.1. Wind 1

Our first wind is predicted to strip gas to either 6 kpc (instantaneous, Figure 10), 9 kpc (integrated, Figure 11), or 11 kpc (integrated to t_{maxRP} Figure 11). Using just the acceleration in the z-direction (right panel of Figure 3), the prediction is 10 kpc only integrated to t_{maxRP}.

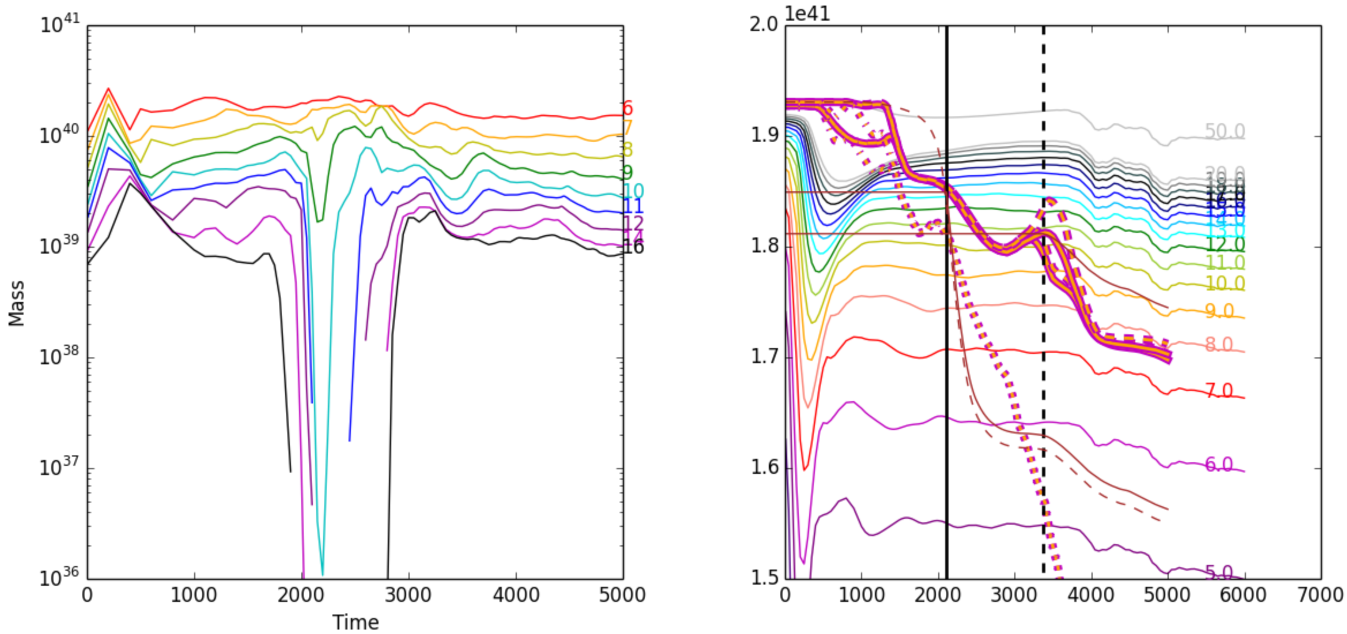

Fig. 12.— Wind 1: **Left Panel:** Here you see that 9 kpc is probably not stripped, 10 kpc probably is stripped, and 11 kpc is definitely stripped for a bit. **Right Panel:** As in Galaxy 1, I would say that ram pressure stripping takes us to the first minimum, just before the dashed vertical line. That looks like 10 kpc at about 3 Gyr, and 12 kpc at later times because this galaxy is not stable. This agrees pretty well with what we see in the left panel, and really isn't too far from our prediction using the integrated ram pressure, and is even better when we only integrate up to t_{maxRP}, although it is best when compared to the acceleration in the wind direction. As before, this continuous stripping calculation doesn't do a great job on this wind.

4.3.2. Wind 2

The second wind has the same shape as the first, but is quite a bit stronger. I did this by changing the density profile of the MW halo, so the orbit (distance and velocity) is unchanged. It is predicted to strip gas to either 3-4 kpc (instantaneous, Figure 10), $\sim$ 5-6 kpc (integrated, Figure 11), or 6-7 kpc (integrated to t_{maxRP} Figure 11). Using just the acceleration in the z-direction (right panel of Figure 3), the prediction is still between 6-7 kpc only integrated to t_{maxRP}.

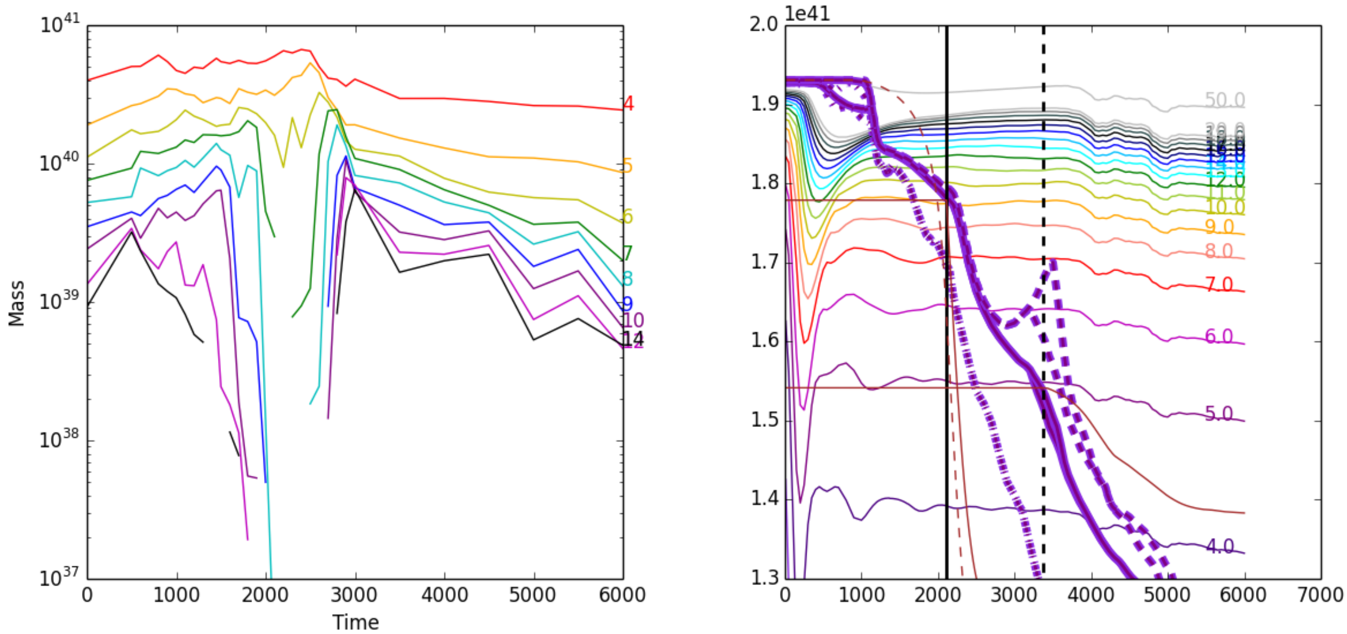

Fig. 13.— Wind 2: **Left Panel:** Here you see that 6 kpc is probably not stripped fine, and 7 kpc is definitely stripped for a bit. **Right Panel:** This panel actually agrees nicely with the prediction by Figure 3 using the total integrated ram pressure, and indicated a bit more stripping than predicted using the integrated RP up to t_{maxRP}. (Just over 5 kpc instead of over 6 kpc).