# THE PHYSICS OF THE STEEL BALL

*An analysis of the properties and rotational capabilities of Gyro Zeppeli's "Steel Balls" from JoJo's Bizarre Adventure: Steel Ball Run in accordance with real-world physics.*

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# INTRODUCTION AND CONTEXT

*JoJo's Bizarre Adventure* is a manga series written and illustrated by Hirohiko Araki. The various story arcs are divided into separate "parts", with seven parts completed and an eighth currently ongoing. Throughout the series, various supernatural powers and events are introduced, including Hamon, a magical martial arts technique used to fight vampires; Stands, psychic manifestations of an individual's fighting spirit; and Spin, a technique used to manipulate and control the rotation of objects.

"Spin" is introduced in Part 7, subtitled as Steel Ball Run, and is used extensively by the character Gyro Zeppeli, who uses the technique to rotate and throw steel balls. Once imbued with Spin, these steel balls can move in ways which would normally be impossible, performing feats such as returning to Gyro after thrown, transferring the rotation to a being's muscles in order to trigger a reflex, boring holes into the ground, and more. Although the Spin technique is unrealistic, it is still grounded in basic rotational physics, so I decided to find its limits.

In one part of the Steel Ball Run manga, Gyro Zeppeli fights against an enemy Stand user named Blackmore. His Stand ability, called Catch the Rainbow (a reference to the song of the same name, produced by Ritchie Blackmore), has the power to suspend raindrops in midair, which he uses to create a shield of raindrops around him that deflects Gyro's steel balls. Gyro eventually defeats him by throwing a steel ball at a raindrop so that the ball continues spinning against it, evaporating the raindrop through friction and travelling on to hit Blackmore directly.

In this project, I will be looking through the Part 7 manga to determine the approximate dimensions of the steel balls, since there is little to no official information on them, and using that data to calculate the limits of a steel ball's rotational potential, along with whether the events of the Catch the Rainbow fight could occur according to real-world physics.

# The “Catch the Rainbow” Fight


THE 'RAINDROPS' THAT ARE IN THE AIR...
BECAUSE OF THE FRICTION CAUSED BY THE SPIN...
BECAUSE OF FRICTION...
...HE DID IT...!
...... ......

## Questions To Be Answered:

1. Are the steel balls hollow or solid?
2. What are the dimensions of the steel balls?
3. What is the maximum spinning speed (angular velocity) of a steel ball, using both physical and human limits?
4. Could a spinning steel ball actually evaporate a static raindrop through friction, as shown in the “Catch The Rainbow” fight?

## Assumptions:

1. The steel balls are perfect spheres (ignoring the grooves).
2. The steel balls are made from mild steel and have a density of 7.87 g/cm^3. *[1]*
3. Whether hollow or solid, the steel balls have uniform mass distributions.
4. Gyro’s steel balls and Wekapipo’s “Wrecking Balls” are the same size (more on this later).

## Methods To Find Dimensions

1. Compare to Gyro by approximate height
2. Size of Johnny’s horse (11-year-old Appaloosa) –> Johnny height -> Gyro height -> steel ball
3. Compare to Holy Corpse eyeball in steel ball
4. Mr. Steel with ruler -> glasses/face -> wrecking ball
5. Compare to size of Valentine’s ear

Note: all sources at end of paper

Sources cited in paper as *[#]*

# HOLLOW OR SOLID?

Are the steel balls hollow or solid?

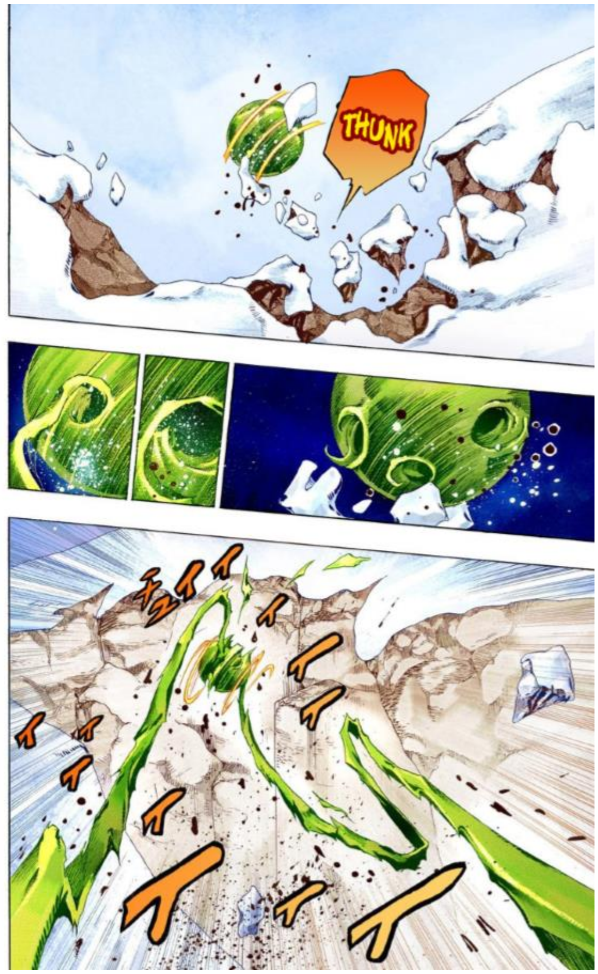
To answer this question, I have found several panels which depict the steel balls being destroyed, in order to determine whether the interior is hollow or solid.

Reference images:

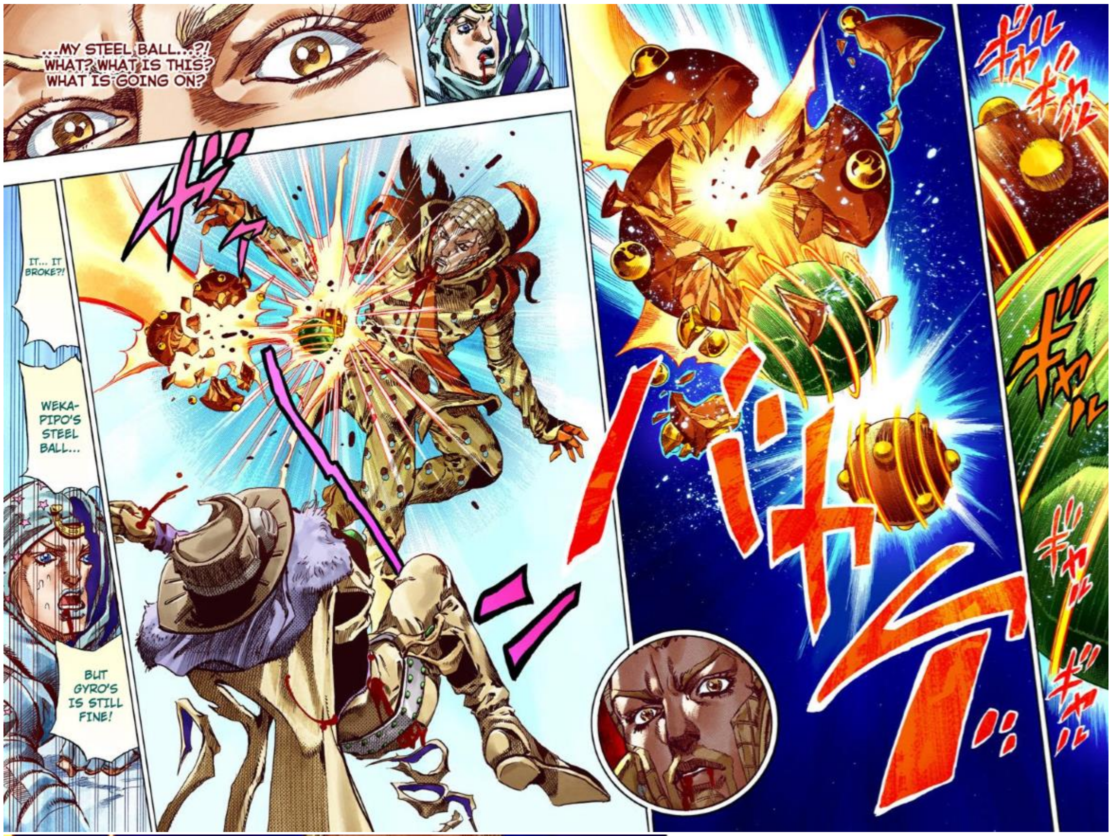

No conclusive view on interior of steel ball.


Steel ball appears possibly hollow, but still inconclusive.

Steel ball appears hollow, but could be misleading shading.




As shown in upper left panel, the steel ball has a solid core. This is the most definitive portrayal of a partially destroyed steel ball, so it is likely that the steel balls are solid.

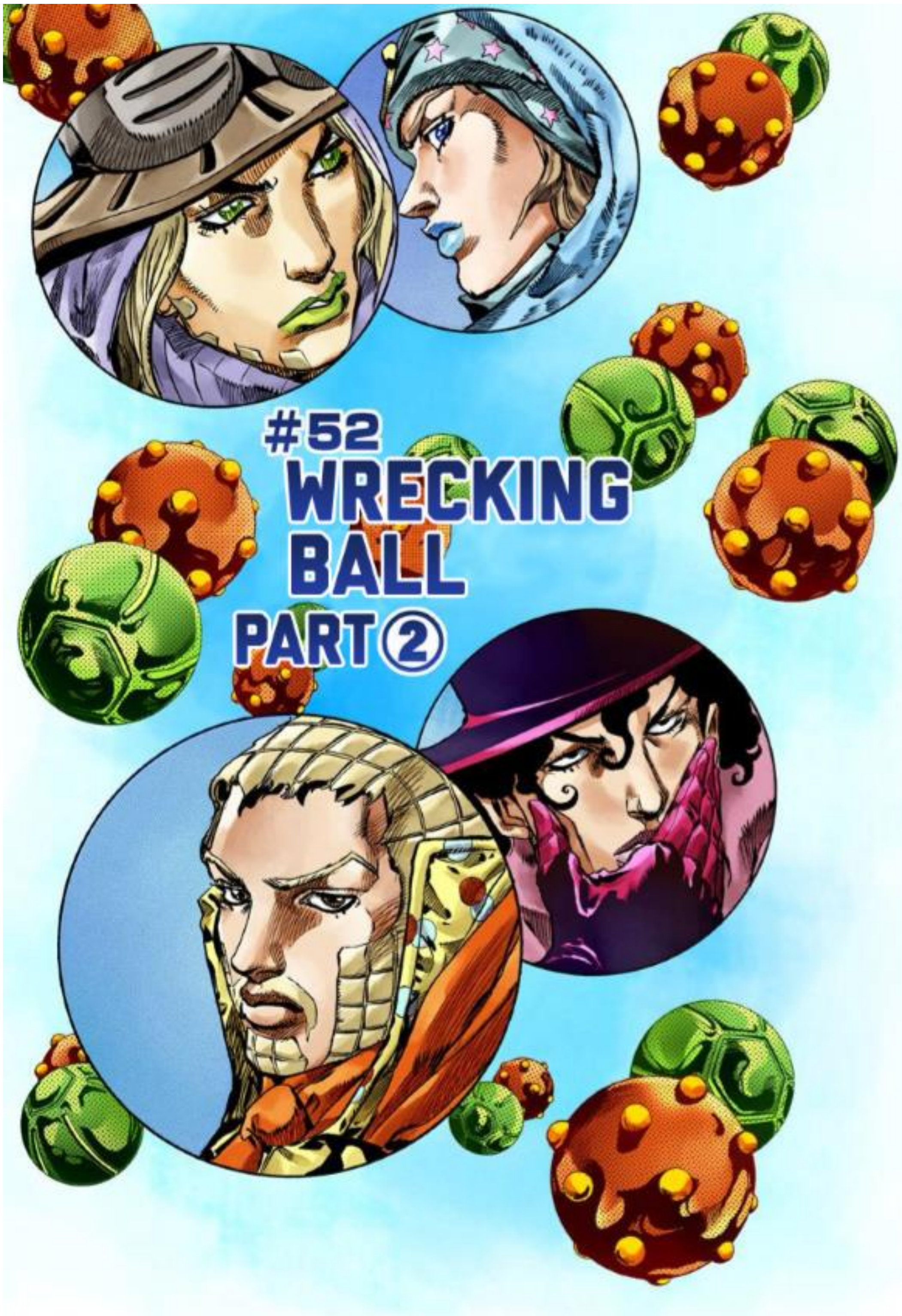



Additionally, as shown in the above pages, Wekapipo's Wrecking Balls are solid. Since the Wrecking Balls are variants of the steel balls Gyro uses, and considering that they are approximately the same size (shown below), it is reasonable to assume that the steel balls are also solid, as they were likely created with similar methods.

## WRECKING BALLS?

Are Gyro’s and Wekapipo’s steel balls the same size?

Reference images:




ギャル
ギャル
ギャル
JOHNNY, GET DOWN!
THAT GUY...! HE'S FROM MY COUNTRY...!
I REMEMBER NOW...
キィィン
シル
ドバッ


When accounting for perspective, the above panels provide evidence that the steel balls and Wrecking Balls are approximately the same size.

# METHOD 1

Compare to Gyro’s height

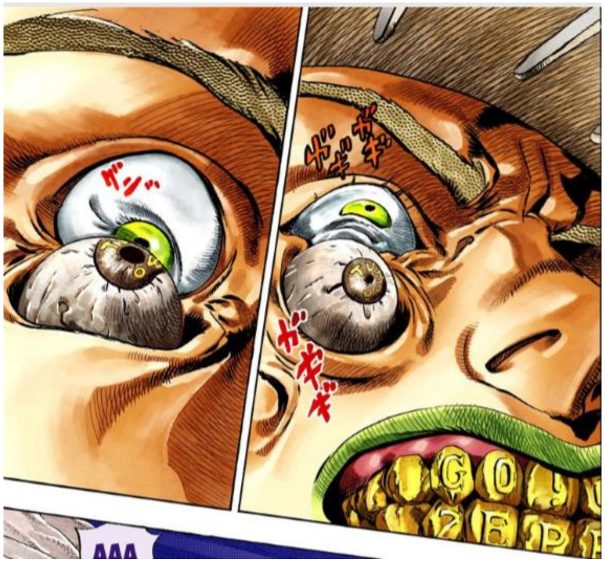
Failed: no official SBR heights

# METHOD 2

I do not want to do this one.

# METHOD 3

Compare to Holy Corpse's eyeball



As shown in the image above, the Holy Corpse's eyeball is approximately the same size as Gyro's eyeball. Human eyeballs are consistently around 2.4 cm wide *[2]*, so we can use images with the eyeball inside of the steel ball to compare dimensions.

Eyeball diameter = 208 px
Opening width = 257 px

Opening width = 137 px
Ball diameter = 287 px

Average diameter of human eyeball = 2.4 cm
Ball diameter = 6.2 cm

# METHOD 4

Stephen Steel with a ruler


I initially expected this to be the easiest and most accurate method of comparison, especially after I had determined that the steel ball and Wrecking Ball were the same size, since the ruler should be a constant length. However, upon analyzing the reference panels, I realized that the ruler was either grossly out of proportion, or used some made-up unit system. As shown in the bottom of the panel on the right, the ruler measures at least 45 units, which I assumed would actually be 50. Since the ruler counts in increments of 5, it clearly uses the metric system, which is further proven by the fact that Magenta Magenta (the man with the gun) asks for the ruler to be moved “2 cm to the left”. The problem arises in what metric unit the ruler uses: the ruler appears to be much shorter than 50 cm, but much longer than 50 mm.

Nevertheless, I attempted to continue with the reference images. When I took the ruler to be 50 cm, comparing it to Stephen Steel's glasses and then comparing the glasses to the Wrecking Ball, I found a diameter of about 17.65 cm, which is obviously inaccurate, since it would make the ball much too big to fit in a hand. Even after comparing the size of various other rulers with the initial proportions of Stephen's face and estimating the actual length of the ruler to be around 30 cm, the calculations resulted in a ball diameter of 10.59 cm, which was still much too large.

In the end, I decided to move on to other methods.

# METHOD 5

Compare to Valentine’s severed ear

The average height of a human ear (from tip to lobe) is 6.3 cm. *[3]*


Ball diameter = 363 px

Ear length = 366 px

Average ear length = 6.3 cm

Ball diameter = 6.3 cm

The two successful comparison methods gave me values of 6.2 cm and 6.3 cm for the diameter of the steel ball. Since these values were so close, I took the average to obtain the approximate diameter of the steel ball as 6.25 cm, and the radius as 3.125 cm.

# CALCULATIONS

Known Variables:

- r = radius = 3.125 cm = 0.03125 m
- $\rho$ = density = 7.85 g/cm$^3$ = 7850 kg/m$^3$
- $F_{tu}$ = ultimate tensile strength (maximum stress a material can withstand before breaking) *[4]*
  - Ultimate tensile strength of mild steel = 440 MPa = 440,000,000 kg/(m*s$^2$) *[1]*
- I = moment of inertia = 2/5m*r$^2$
- V = volume = 4/3π*r$^3$

Unknown Variables:

- m = mass (kg)
- v = translational velocity (m/s)
- ω = angular velocity (rad/s)

Relevant Equations:

- $\sigma_t = \rho r^2 \omega^2$
  - $\sigma_t$ = tensile stress on the rim of a cylinder *[5]*
- $v = r\omega$
- $\sigma_t \leq F_{tu}$
  - Stress on a material must be less than the maximum stress it can endure, or it will break.
- $\rho = \frac{m}{V}$

What is the maximum rotational velocity of a steel ball by physical limits?

- When a steel ball is spinning, the outer edge on the "equator" of the ball has the highest translational velocity of any part of the ball.
  - We can treat the "equator" of the steel ball as a very thin cylinder for the purposes of using these equations, since it acts as a limit for maximum edge velocity.
- The equation for tensile stress can be rewritten as $v^2 = \frac{\sigma_t}{\rho}$

- The maximum edge velocity occurs when the stress on the spinning edge is at its highest, which is equal to the material's ultimate tensile strength. $(\sigma_t = F_{tu})$
- ${v_{max}}^2 = \frac{F_{tu}}{\rho}$
- $v_{max} = \sqrt{\frac{440{,}000{,}000\frac{kg}{m*s^2}}{7850\frac{kg}{m^3}}}$
- $v_{max} = 236.751\frac{m}{s}$
  - For reference, the speed of sound through air is 343 m/s
- $\omega_{max} = \frac{v_{max}}{r} = \frac{236.751\frac{m}{s}}{0.03125\,m}$
- $\omega_{max} = 7576.0266\frac{rad}{s}$
- Maximum rotational kinetic energy = $\frac{1}{2}I * \omega^2$
- $RKE_{max} = \frac{1}{2}\left(\frac{2}{5}m * r^2\right)\left(7576.0266\frac{m}{s}\right)^2$
  - $m = \rho * V$
  - $m = 7850\frac{kg}{m^3} * \frac{4}{3}\pi(0.03125\,m)^3$
  - $m = 1.0035\,kg$
- $RKE_{max} = \frac{1}{2}\left(\frac{2}{5}(1.0035\,kg)(0.03125\,m)^2\right)\left(7576.0266\frac{m}{s}\right)^2$
- $RKE_{max} = 11249.2\,J$

<u>What is the maximum rotational velocity of a steel ball by human limits?</u>

- This part is more challenging, both because I can't find any real documentation on how fast a human can spin a steel ball, and because Gyro uses what is essentially magic to spin the ball, so limits observed in reality may not even apply.
- Regardless, I am using the upper limits of the velocity and angular speed for an MLB fastball to find how much energy the pitcher transfers to the baseball, then relating that to throwing a steel ball.
- Fastball data:
  - Fastest fastball record = 108 mph (by Nolan Ryan)

- According to this study *[6]*, the spin of a fastball could increase by up to 26.551 RPM for every 1 mph increase in its pitch velocity, so a speed of 108 mph could result in around 2867.5 RPM.
- Mass of baseball = 0.1455 kg
- Radius of baseball = 0.037 m
- Moment of inertia of a baseball = $2/5m*r^2$ = $2/5(0.1455)(0.037)^2 = 7.968*10^{-5}$ kg*m$^2$

- $KE_{net} = \frac{1}{2}mv^2 + \frac{1}{2}I\omega^2$
  - $v = 108\ mph = 48.2803\frac{m}{s}$
  - $\omega = 2867.5\ RPM = 300.28\frac{rad}{s}$
- $KE_{net} = \frac{1}{2}(0.1455\ kg)\left(48.2803\frac{m}{s}\right)^2 + \frac{1}{2}(7.968 * 10^{-5}\ kg * m^2)\left(300.28\frac{rad}{s}\right)^2 = 173.17\ J$ delivered to the ball by the pitcher
- $173.17\ J = \frac{1}{2}I_{steel\ ball}\ \omega_{max}^2$
- $\omega_{max} = \sqrt{\frac{2(173.17\ J)}{3.920*10^{-4}\ kg*m^2}}$
- $\omega_{max} = 939.97\frac{rad}{s}$ for a stationary, spinning steel ball
  - *Note: while a pitcher obviously could not spin a ball with the same energy used to throw it, in the Catch the Rainbow fight, the steel ball is thrown normally by Gyro, then stops travelling when it collides with the raindrop but continues spinning. Thus, if we consider the distance between Gyro and the raindrop to be negligible, roughly the same amount of energy would be delivered from the ball to the raindrop regardless of how it was thrown.*

Could a spinning steel ball evaporate a raindrop suspended in the air?

- Assuming a spherical raindrop of uniform density with a diameter of 5 mm *[7]*,
  - $V_r = \frac{4}{3}\pi(0.005\ m)^3 = 5.236 * 10^{-7}m^3$
  - Density of water = 997 kg/m$^3$

- $m_r = \rho * V_r$
- $m_r = 997\frac{kg}{m^3} * (5.236 * 10^{-7}m^3)$
- $m_r = 5.22 * 10^{-4}\ kg = 0.522\ g$

- Average temperature of rainwater = 14°C *[8]*
  - Boiling point of water = 100°C
  - Specific heat of water = 4.186 J/g°C
    - 100 – 14 = 86°C rise
  - $86°C * 4.186\frac{J}{g°C} * 0.552\ g = 187.93\ J$ to raise raindrop to 100°C
- Heat of vaporization of water = 2257 J/g at 100°C
  - $2257\frac{J}{g} * 0.522\ g = 1178.22\ J$ to evaporate raindrop at boiling point
- Total energy required to evaporate raindrop = 187.93 J + 1178.22 J = 1366.15 J
- Maximum energy using physical limits = 11249.2 J > 1366.15 J
- Maximum energy using human limits = 173.17 J < 1366.15 J

## CONCLUSIONS

1. Gyro’s steel balls are probably solid.
2. A steel ball has a radius of approximately 3.125 cm and a mass of 1.0035 kg.
3. A steel ball could theoretically spin at up to 7576.0266 rad/s (72435.73 RPM) without breaking apart.
4. If a professional baseball pitcher spun a steel ball with the same amount of energy as if they had thrown a fastball, it could spin at up to 939.97 rad/s (8976.05 RPM).
5. While a steel ball spinning as fast as physically possible could evaporate a raindrop by transferring energy through friction, a human would most likely be unable to throw the steel ball with enough energy to accomplish this.

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