Separation in three-dimensional steady flows

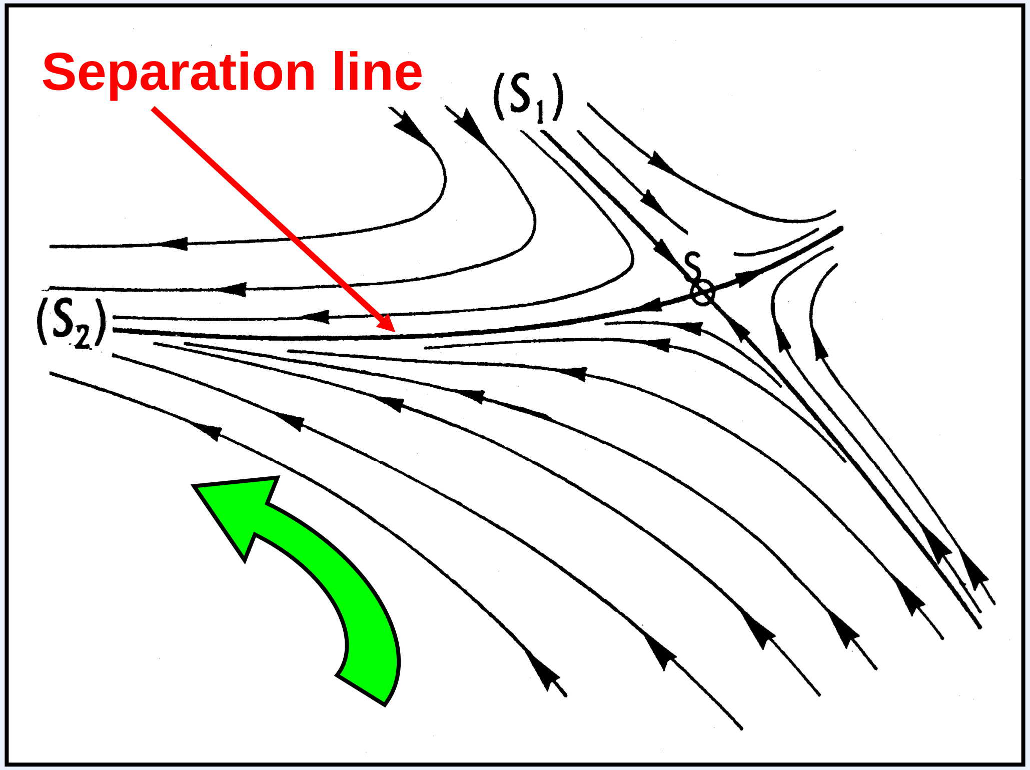
Part 2 : DETACHMENT AND ATTACHMENT SEPARATION LINES

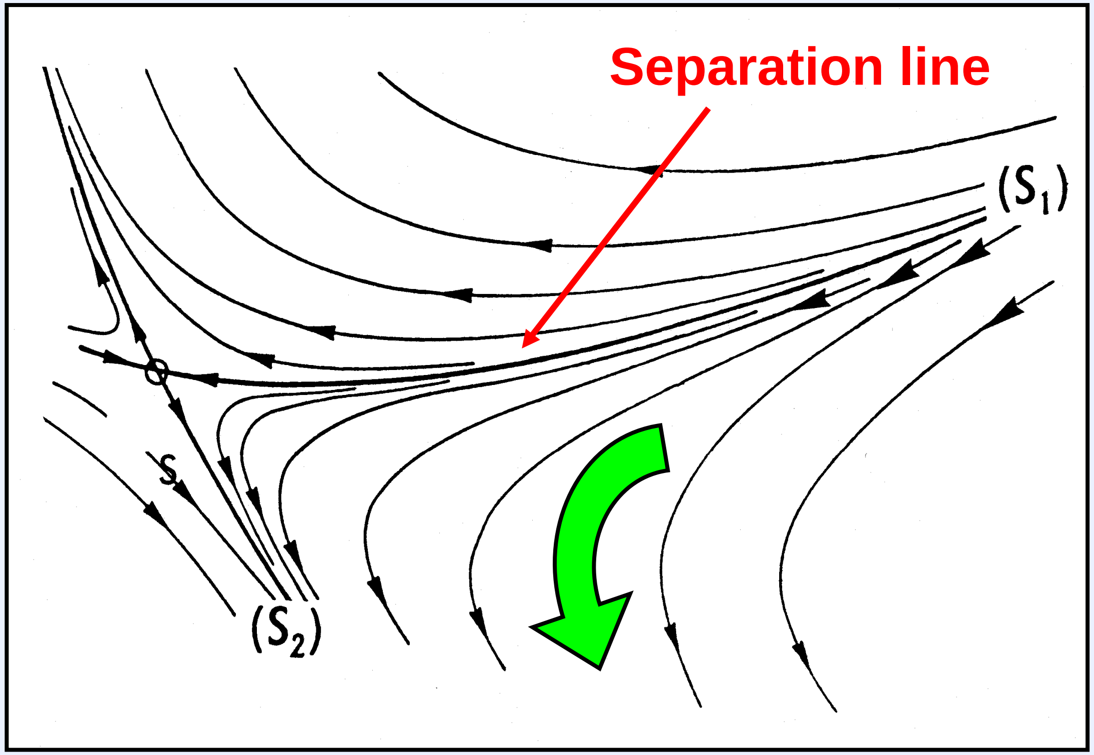
DETACHMENT AND ATTACHMENT SEPARATION SURFACES

ONERA
THE FRENCH AEROSPACE LAB

Separation lines or separatrices

- A separation line is a skin friction line going through a saddle point.
- According to the flow direction, it is associated either to a detachment or an attachment process.





Detachment type (or separation)

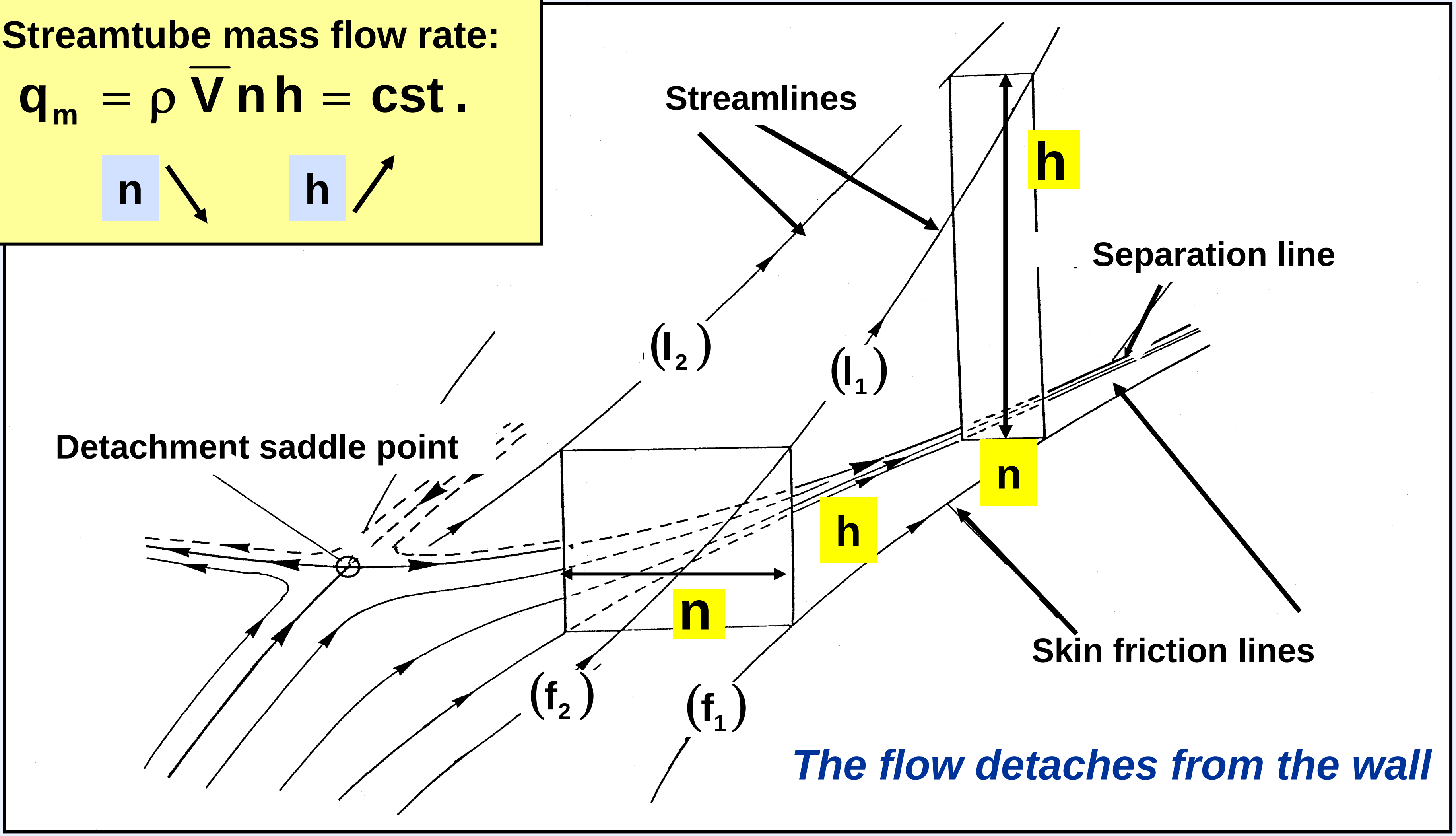
Attachment type

Flow in the vicinity of a detachment line

Streamtube mass flow rate:

$$q_m = \rho \overline{V} n h = cst.$$

n ↘ h ↗



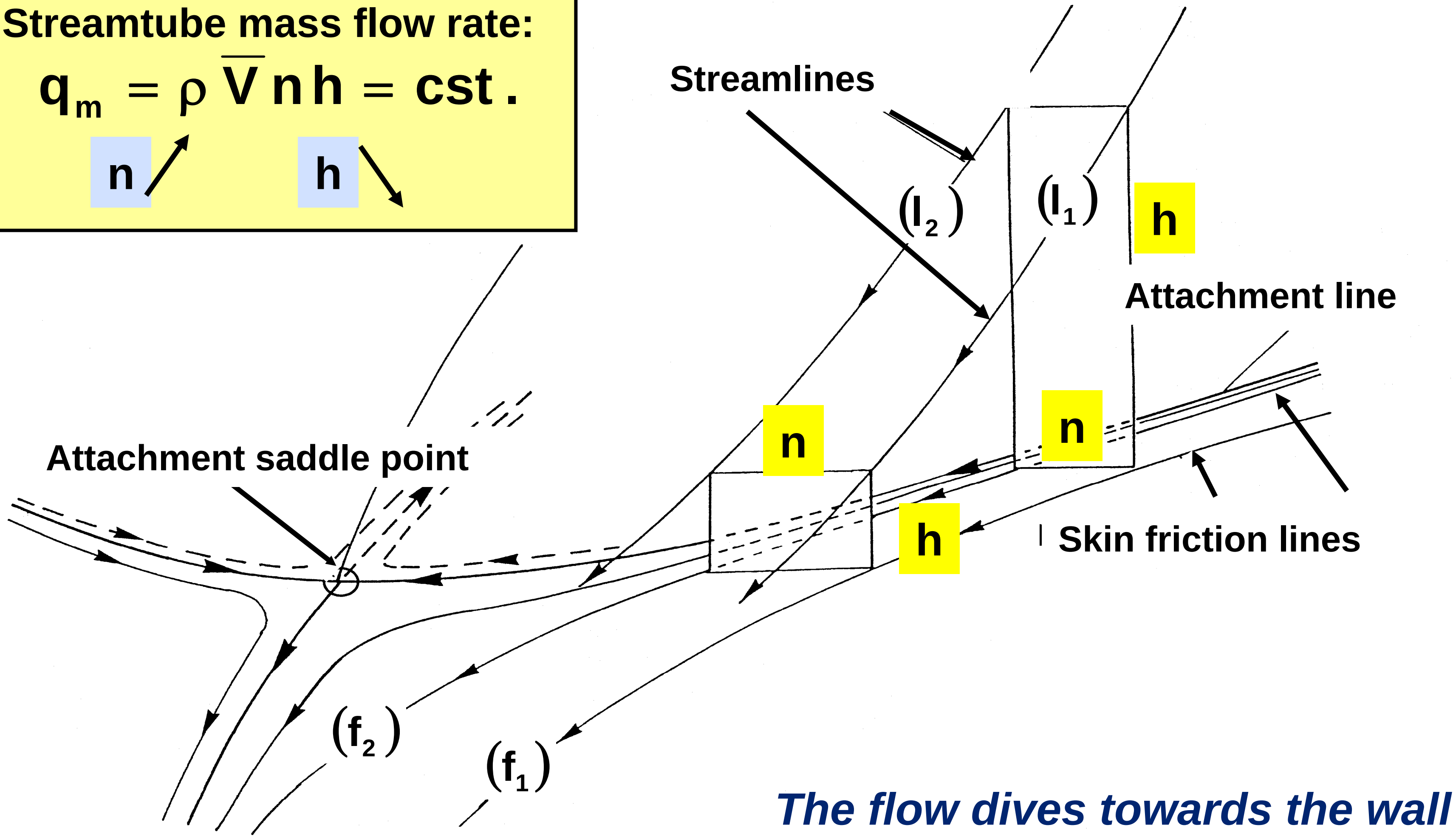
Convergence of the skin friction lines when approaching the separation line entails a vertical dilatation of the streamtube: the flow springs up from the wall or detaches.

Flow in the vicinity of an attachment line

Streamtube mass flow rate:

$$q_m = \rho \overline{V} n h = cst.$$

n ↗ h ↘

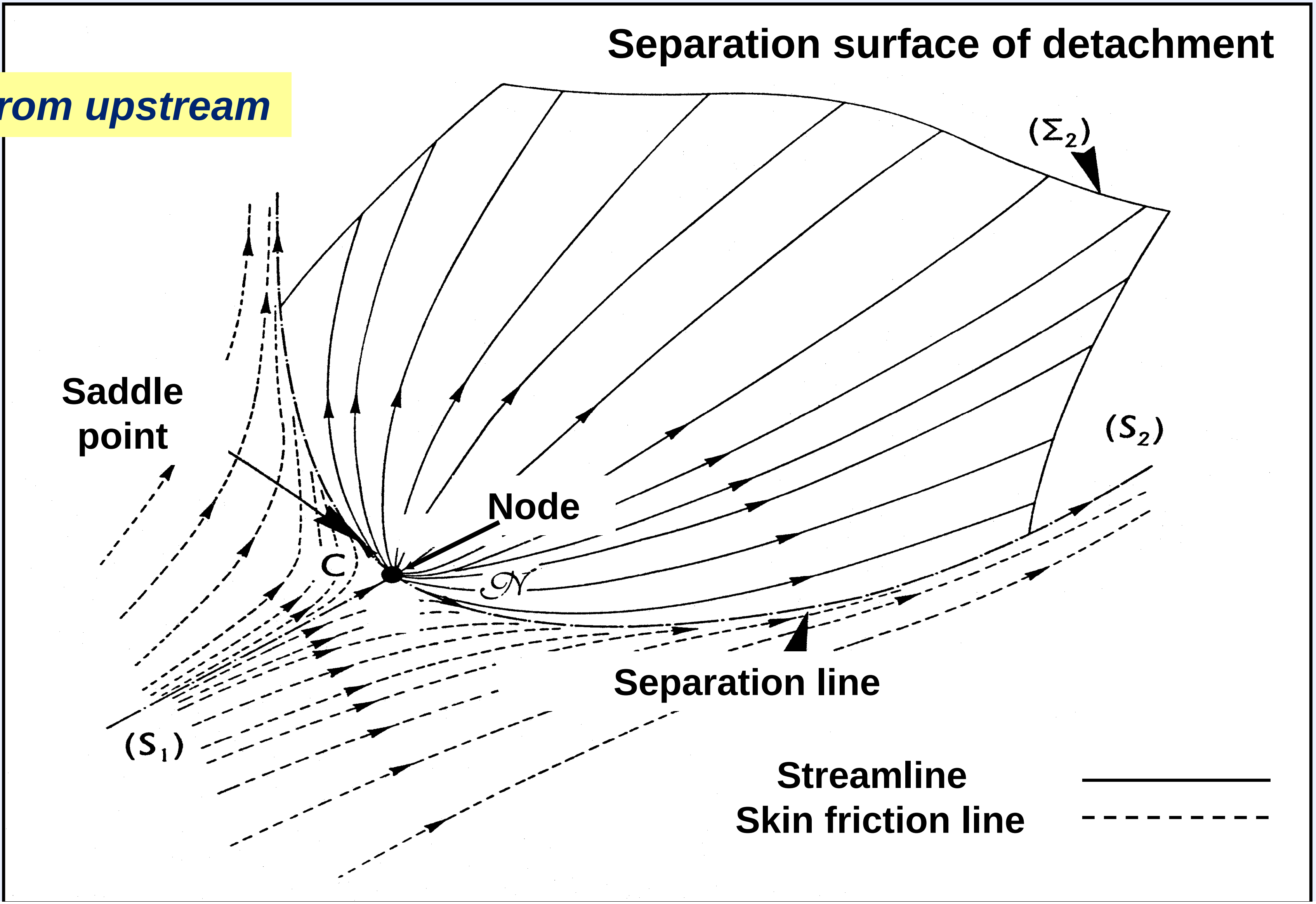


The flow dives towards the wall

Divergence of the skin friction lines when streaming away from the separation line entails a vertical contraction of the streamtube: the flow dives towards the wall and attaches.

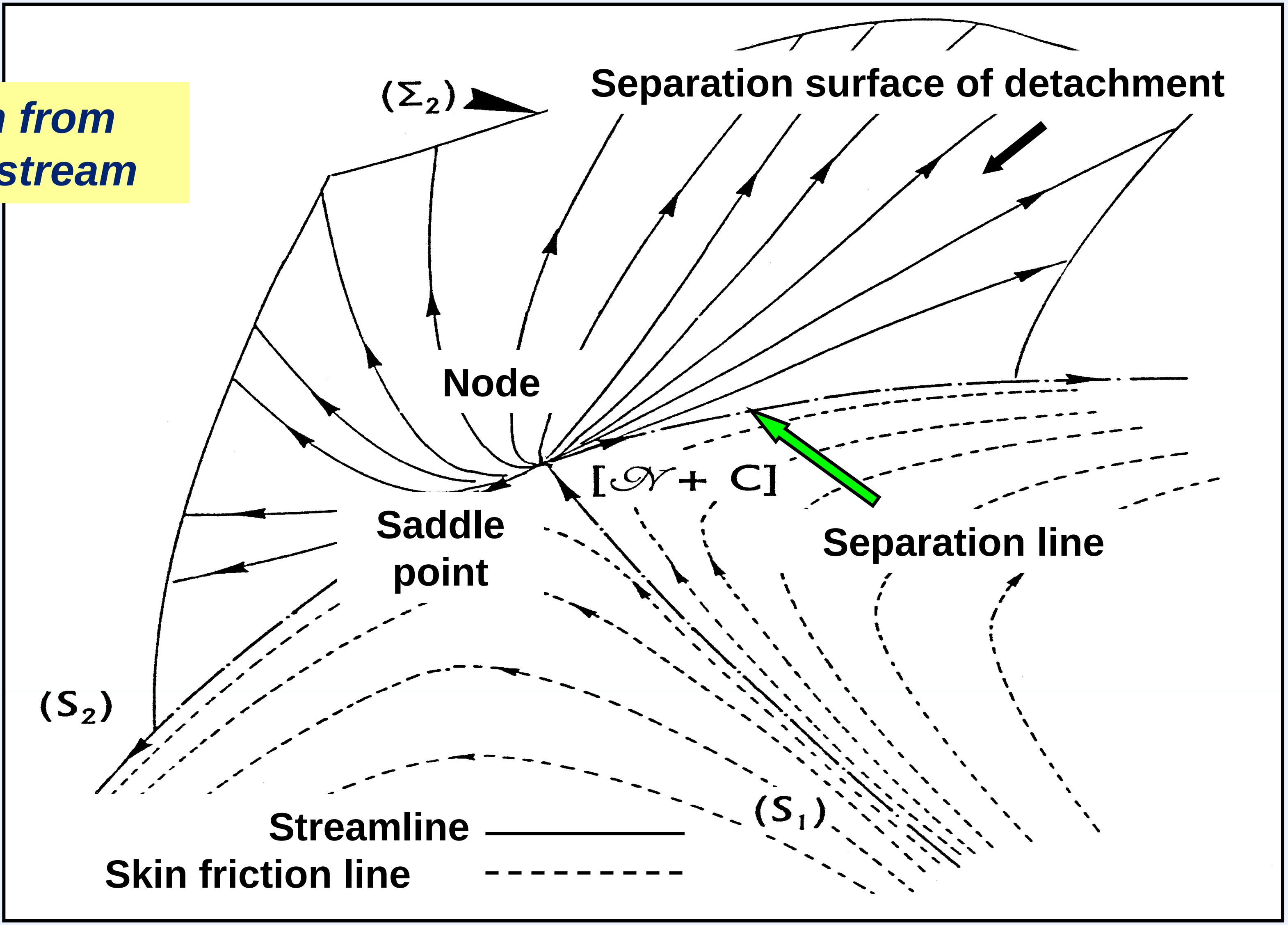
Topology in the vicinity of detachment. The separation streamsurface

Seen from upstream



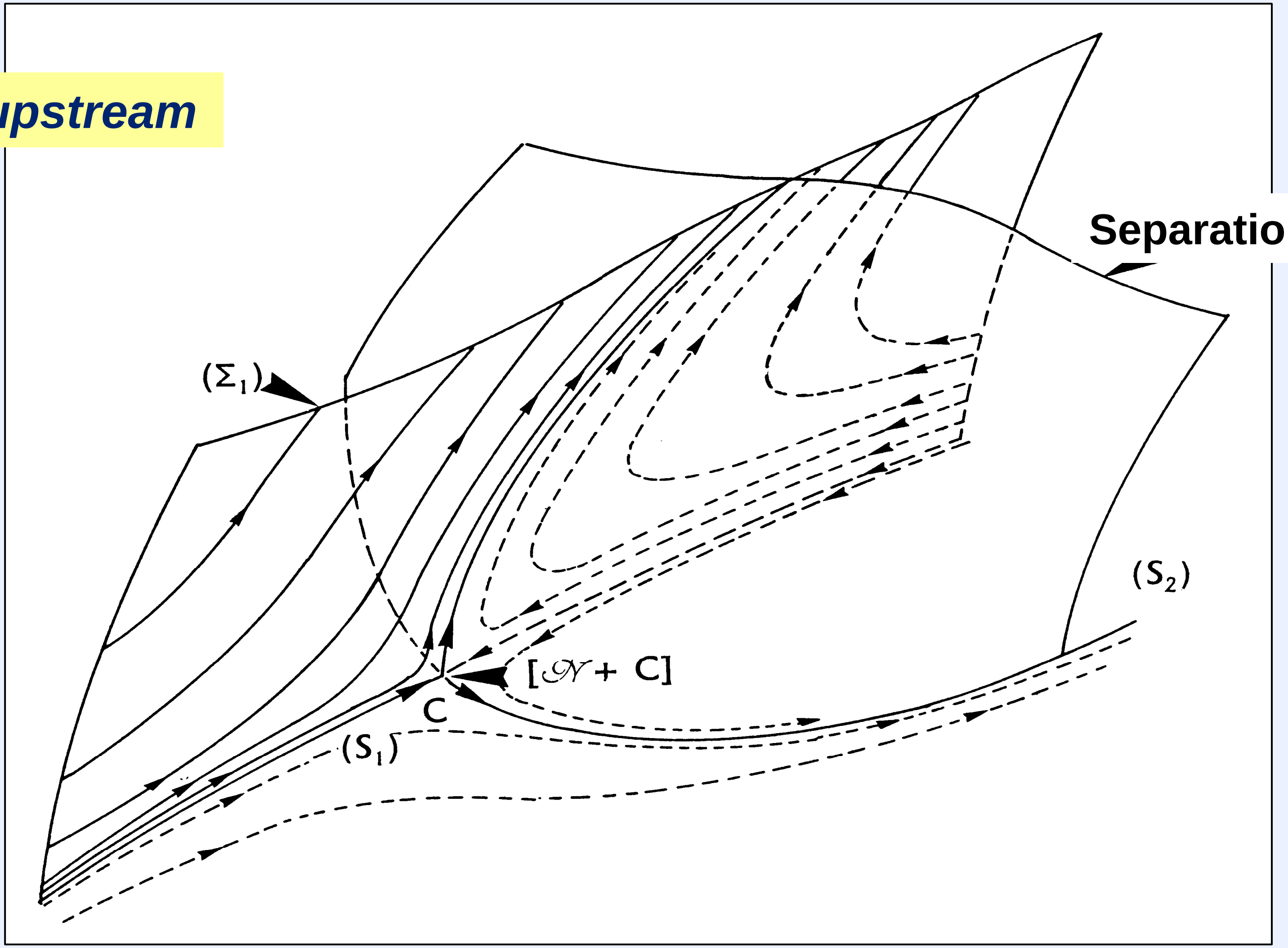
Topology in the vicinity of detachment. The separation streamsurface

Seen from downstream



Topology in the vicinity of detachment. The separation streamsurface

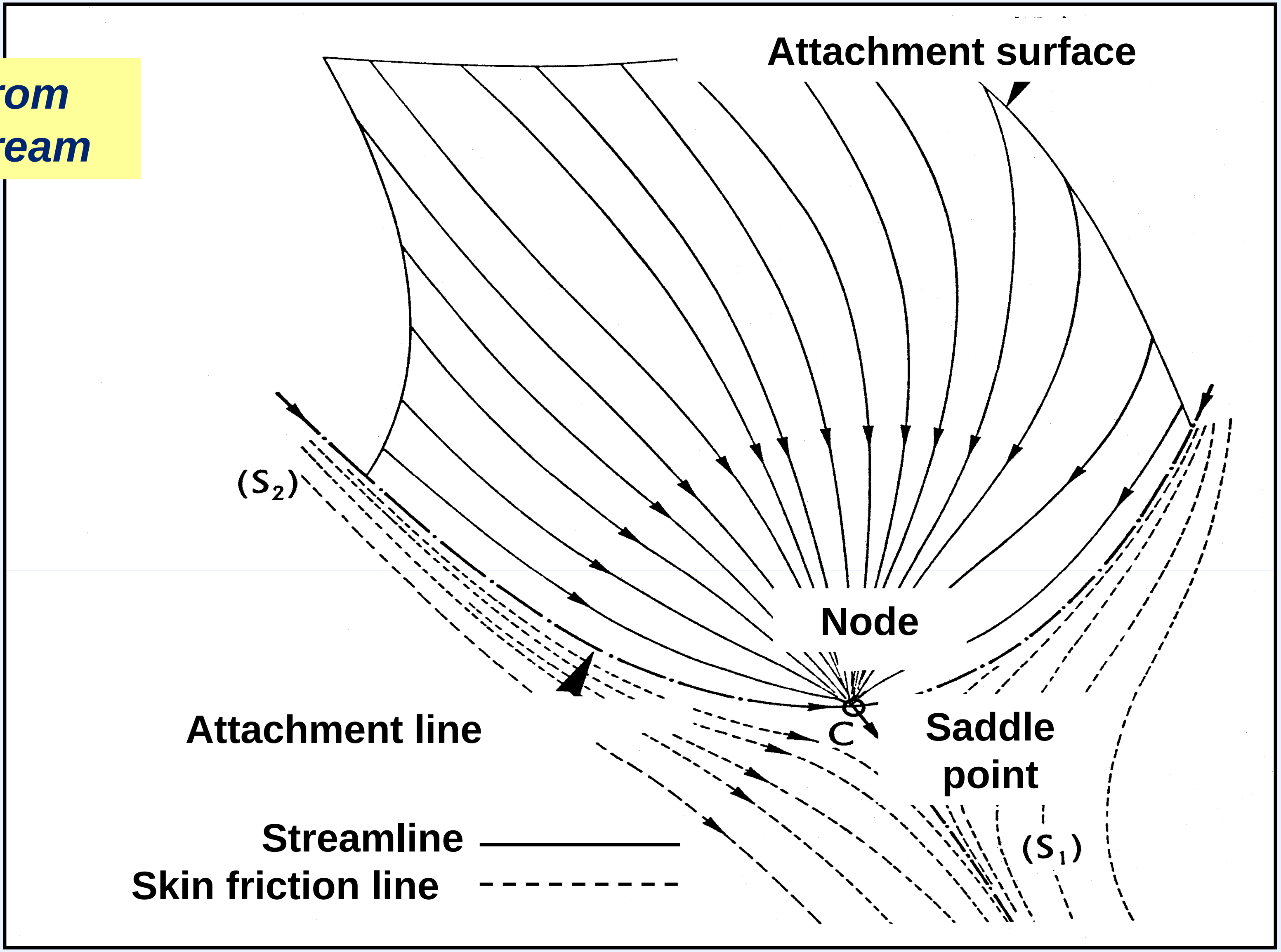
Seen from upstream



Intersection of the separation surface of detachment and of the second separation surface

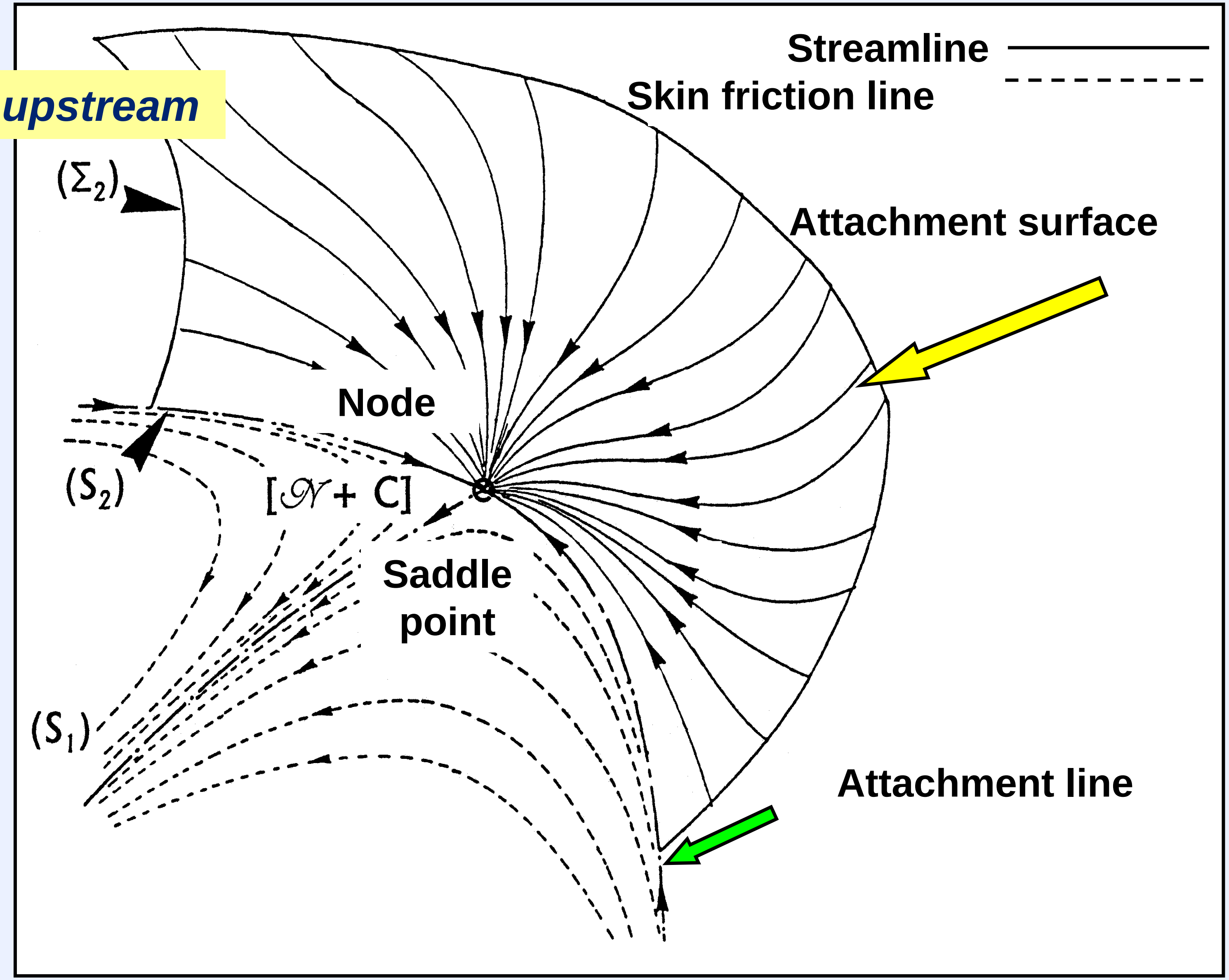
Topology in the vicinity of attachment. The separation streamsurface

Seen from downstream

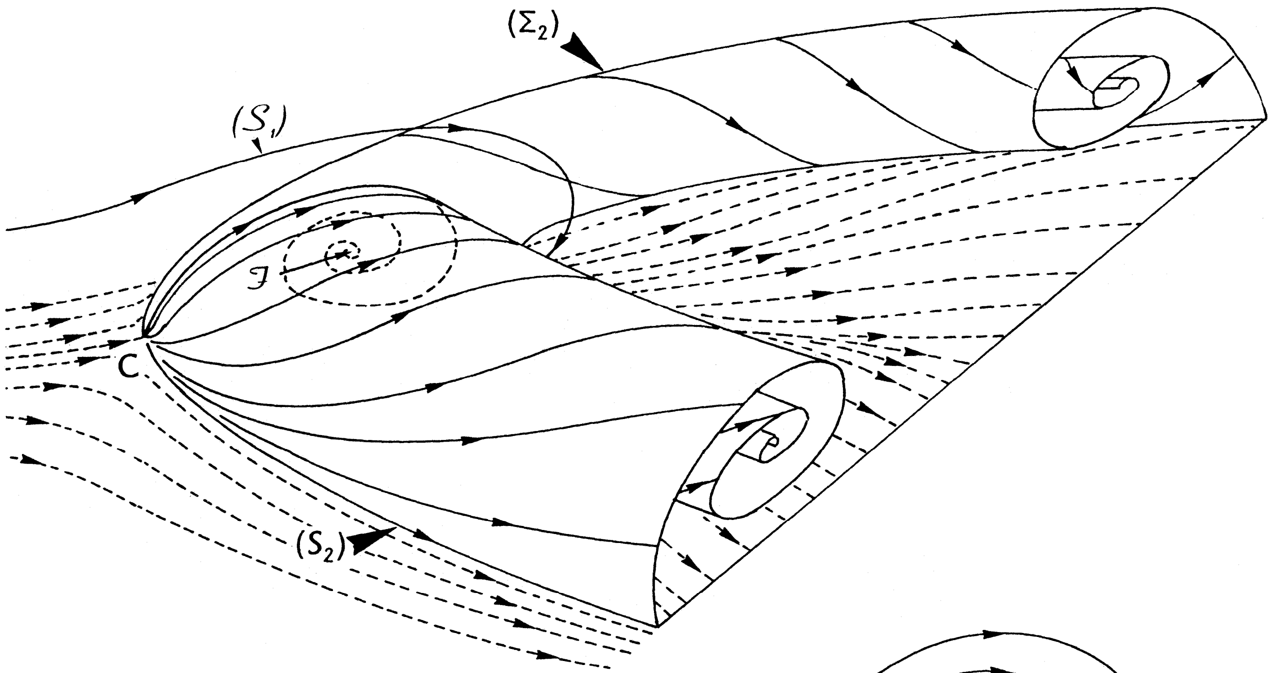


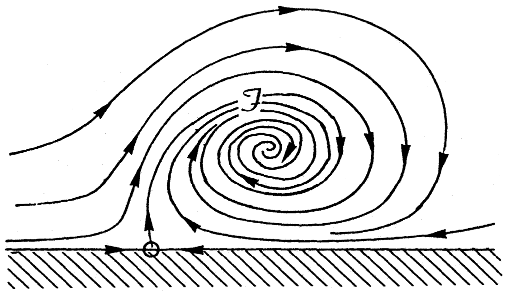
Topology in the vicinity of attachment. The separation streamsurface

Seen from upstream



Formation of a horseshoe vortex

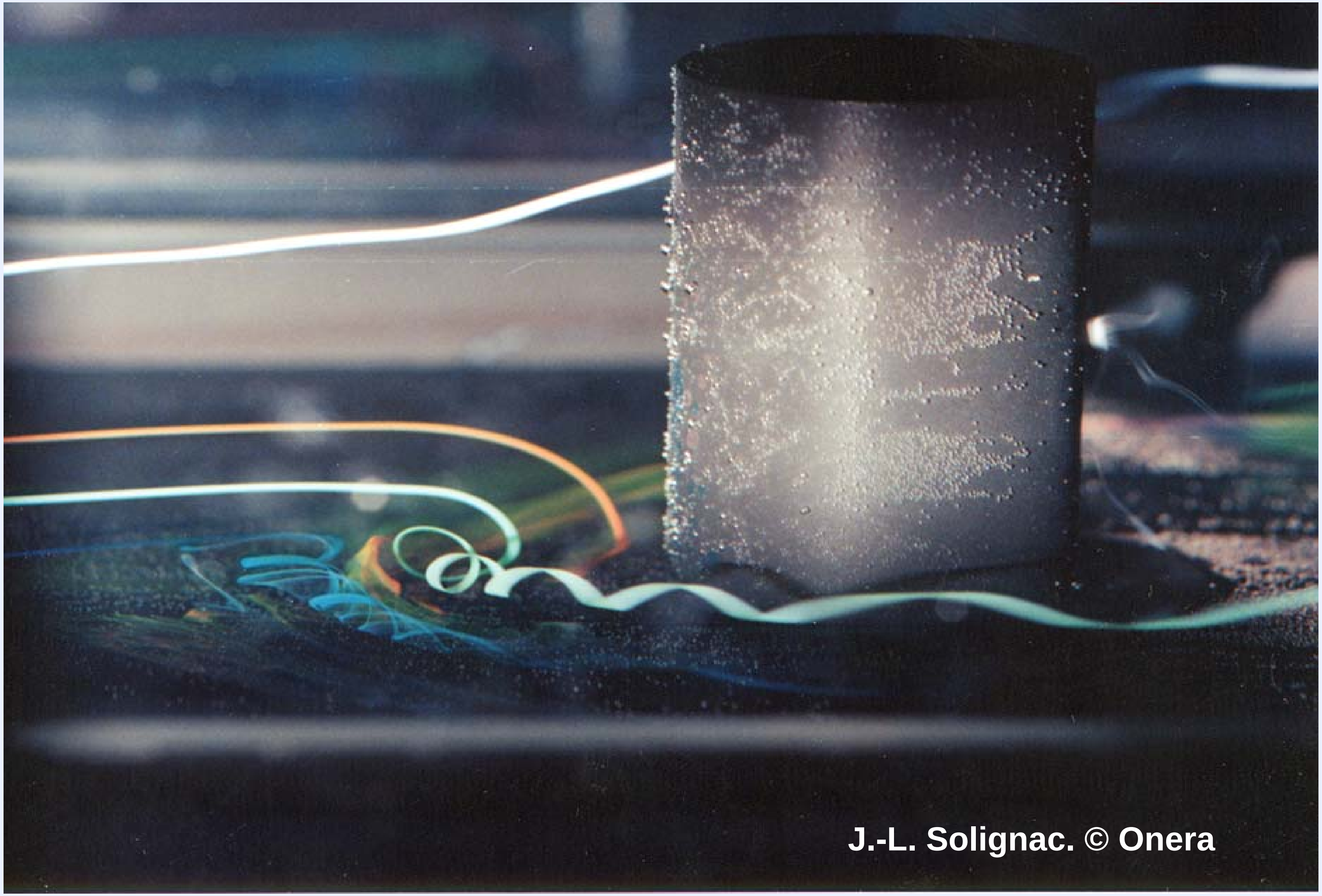




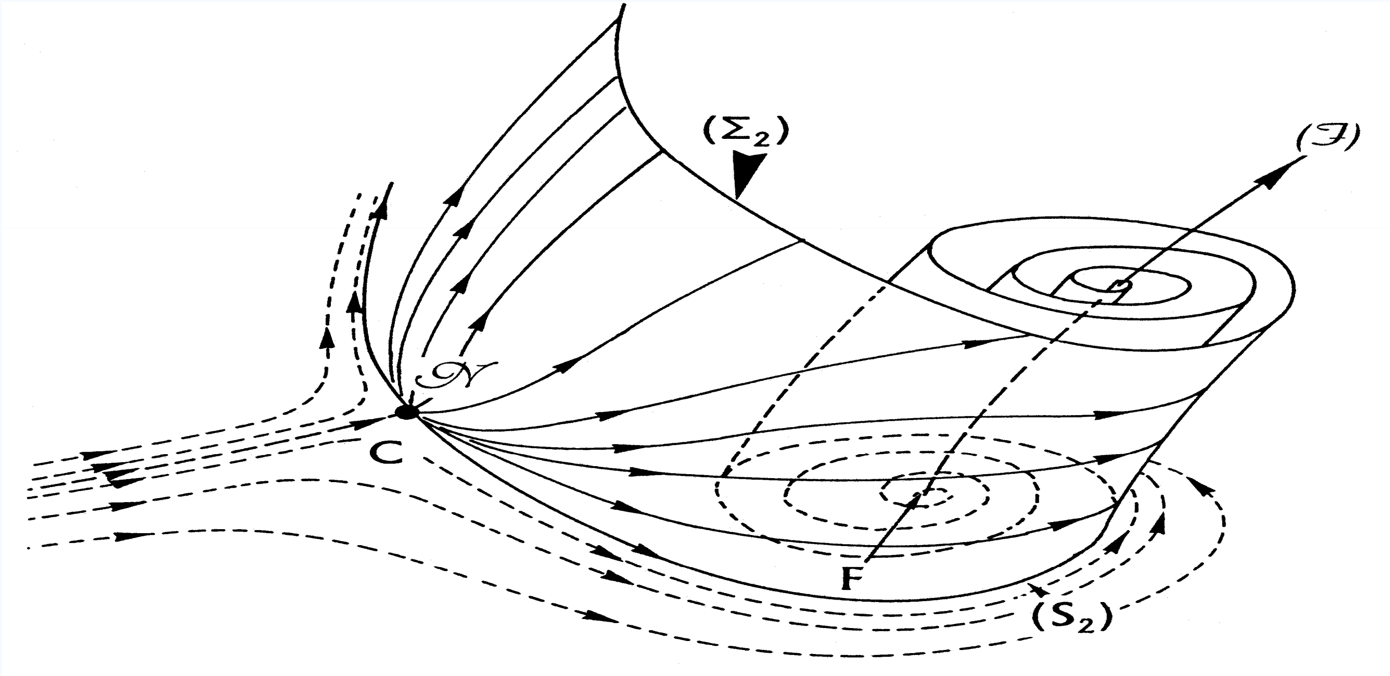
Section by a normal plane downstream of the structure

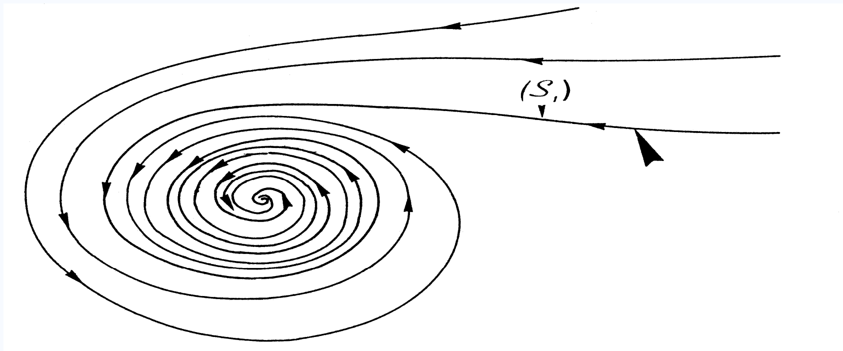
Rolling up of the separation surface of detachment

Horseshoe vortex. Detachment in front of an obstacle



Formation of a tornado like vortex





Section by a plane out of the body surface

Rolling up of the separation surface of detachment

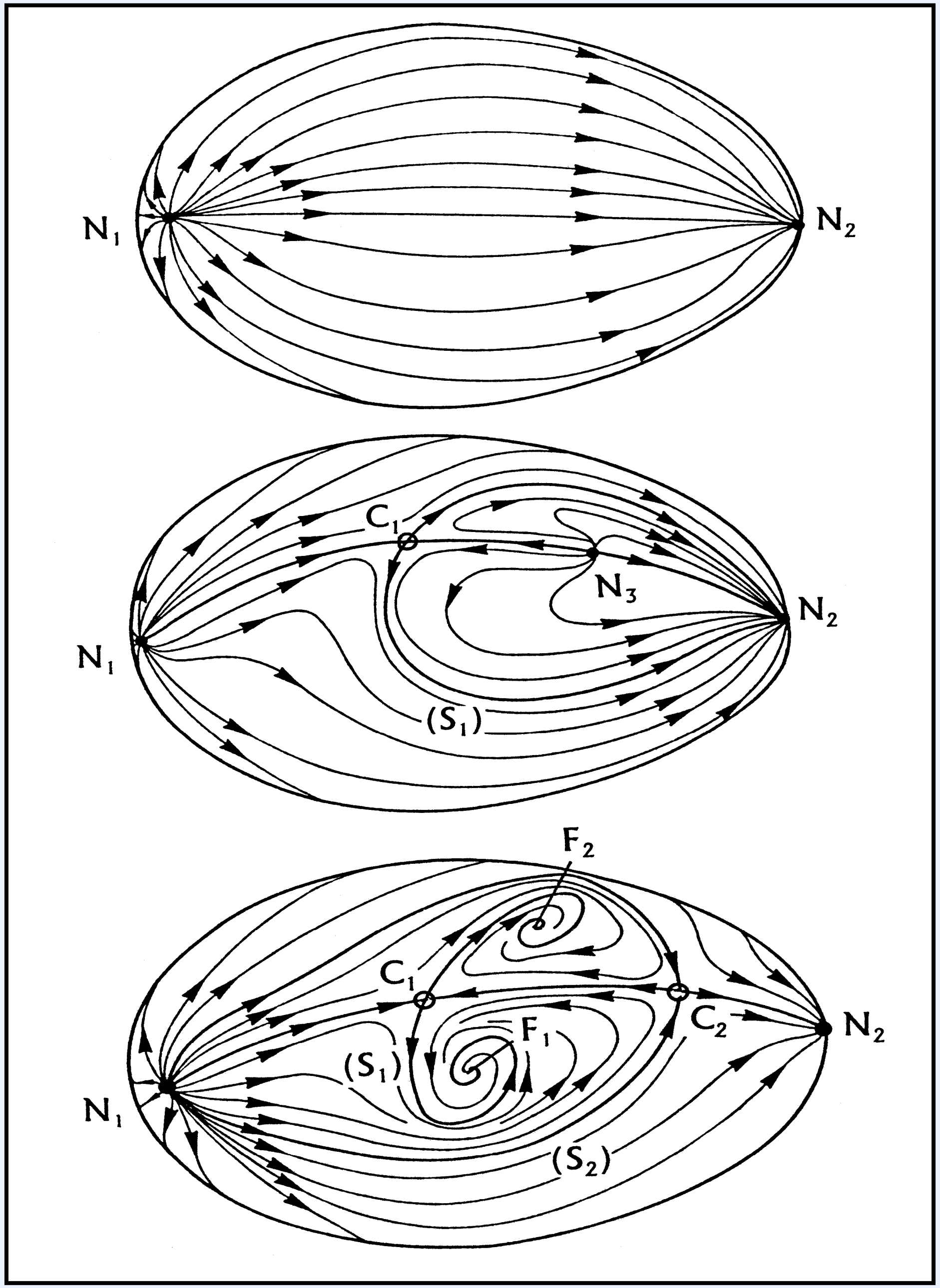
Tornado like vortex

Separation on a simply connected body

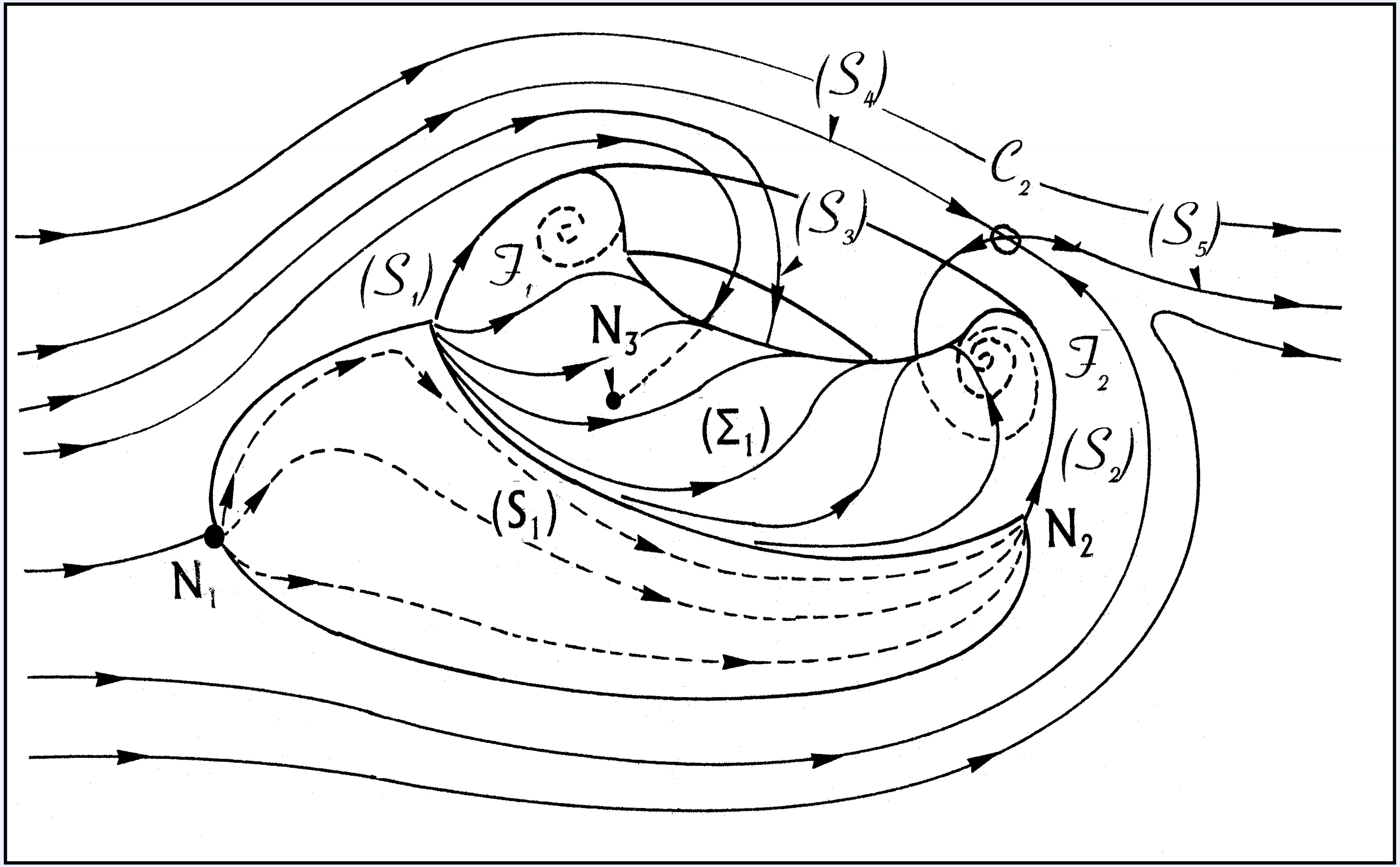
Non separated (or attached) flow

Separated flow with 1 saddle point and 3 nodes

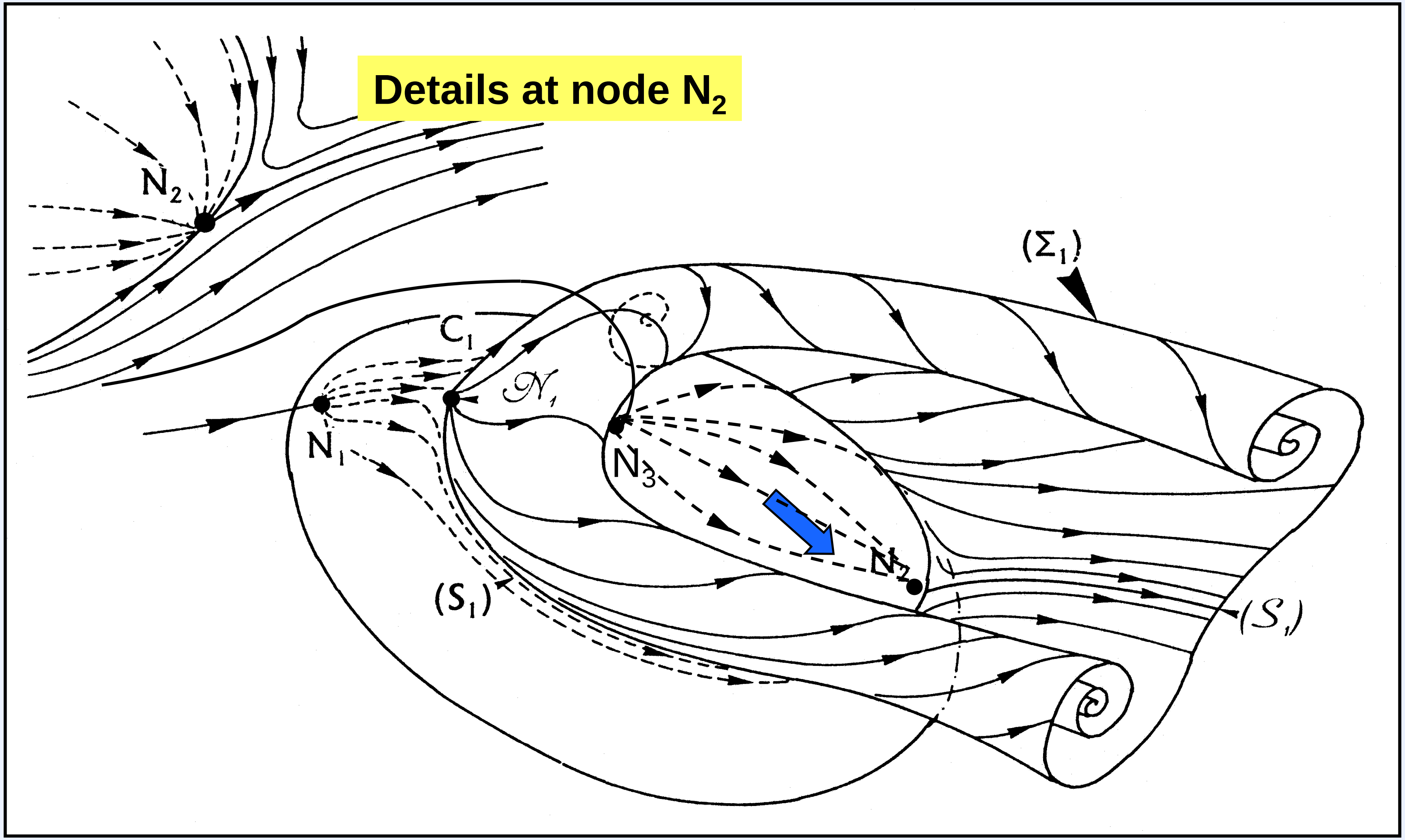
Separated flow with two saddle points, 2 foci and 2 nodes



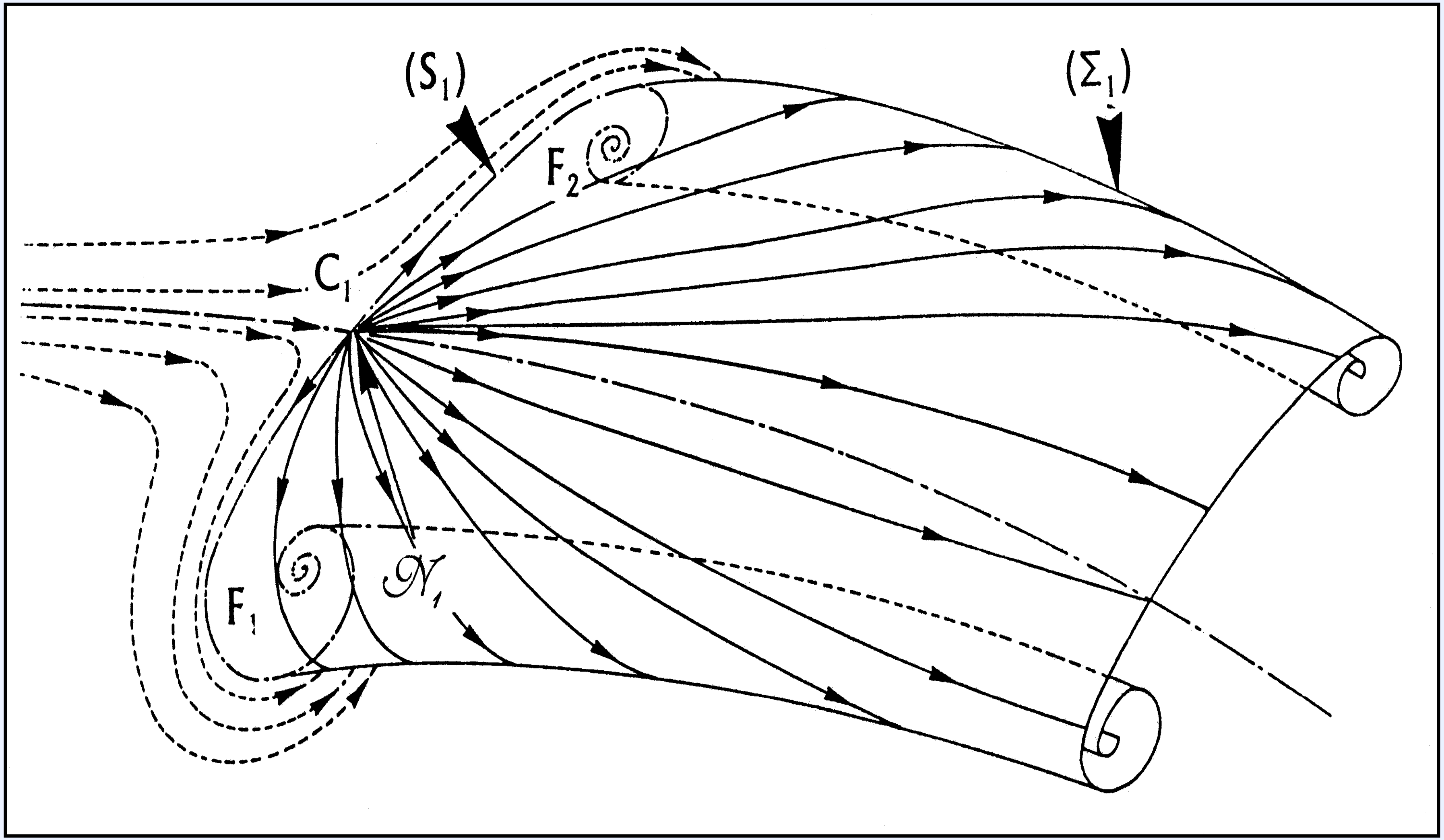
Separation (detachment type) with one saddle point and three nodes. Formation of a ring type vortex



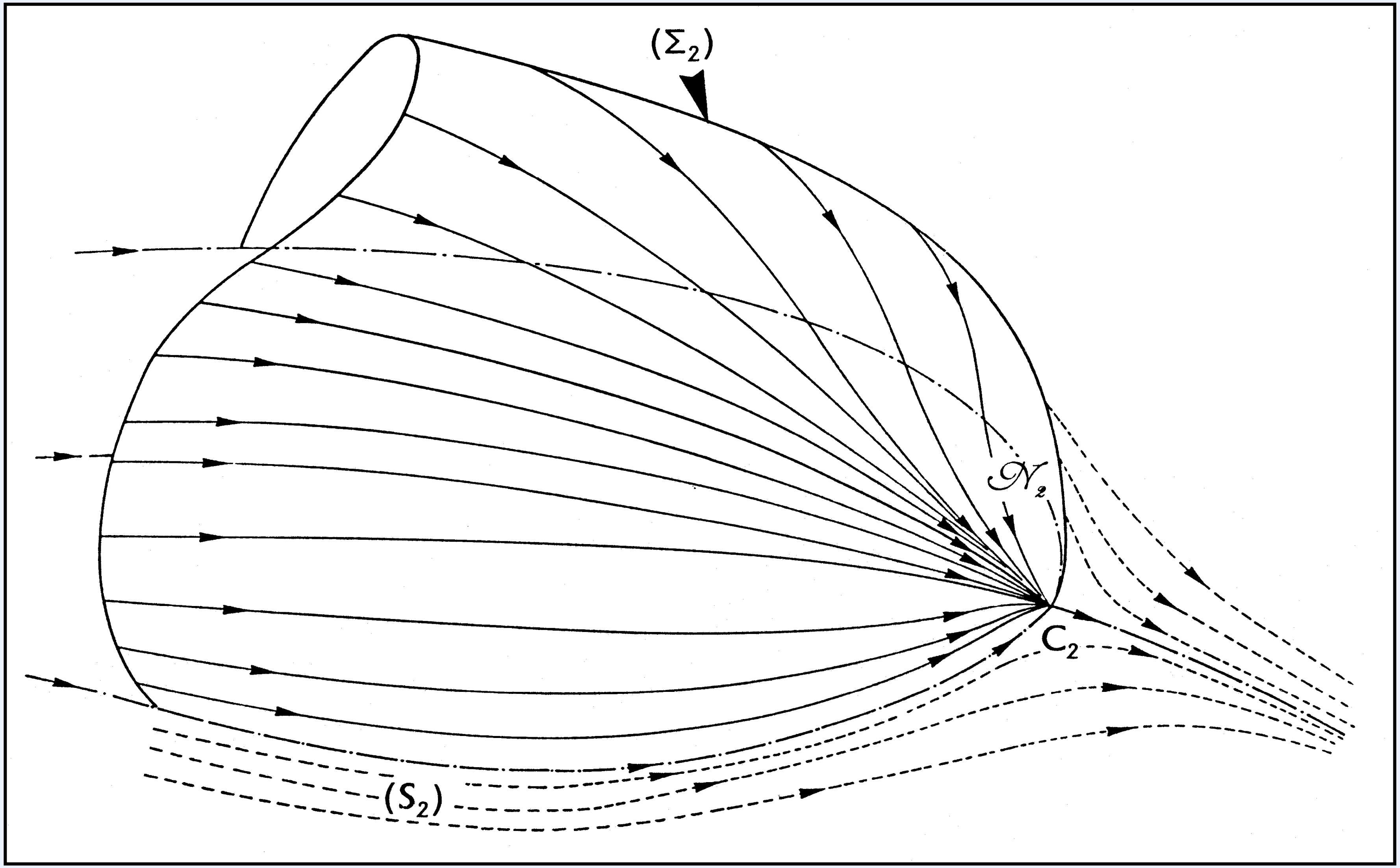
Separation (detachment type) with one saddle point and three nodes. Formation of an open – or horseshoe - vortex



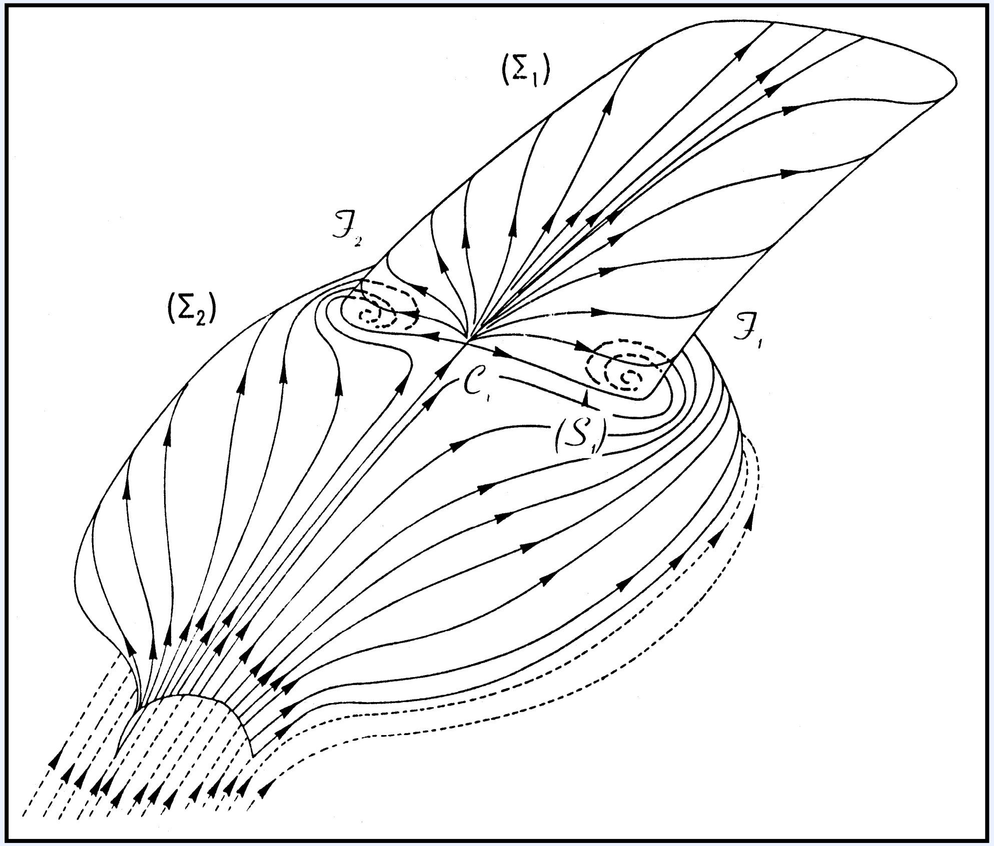
Separation with two saddle points and two foci.
The separation surface of detachment



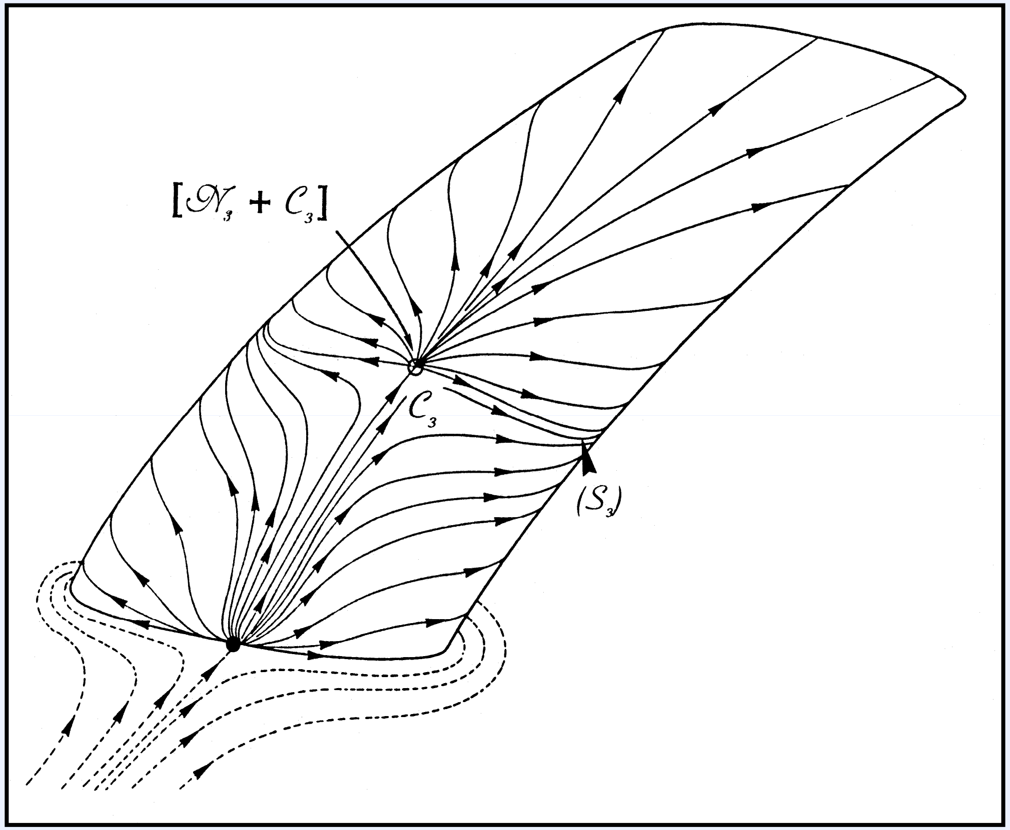
Separation with two saddle points and two foci. The attachment surface



Detachment with two saddle points and two foci

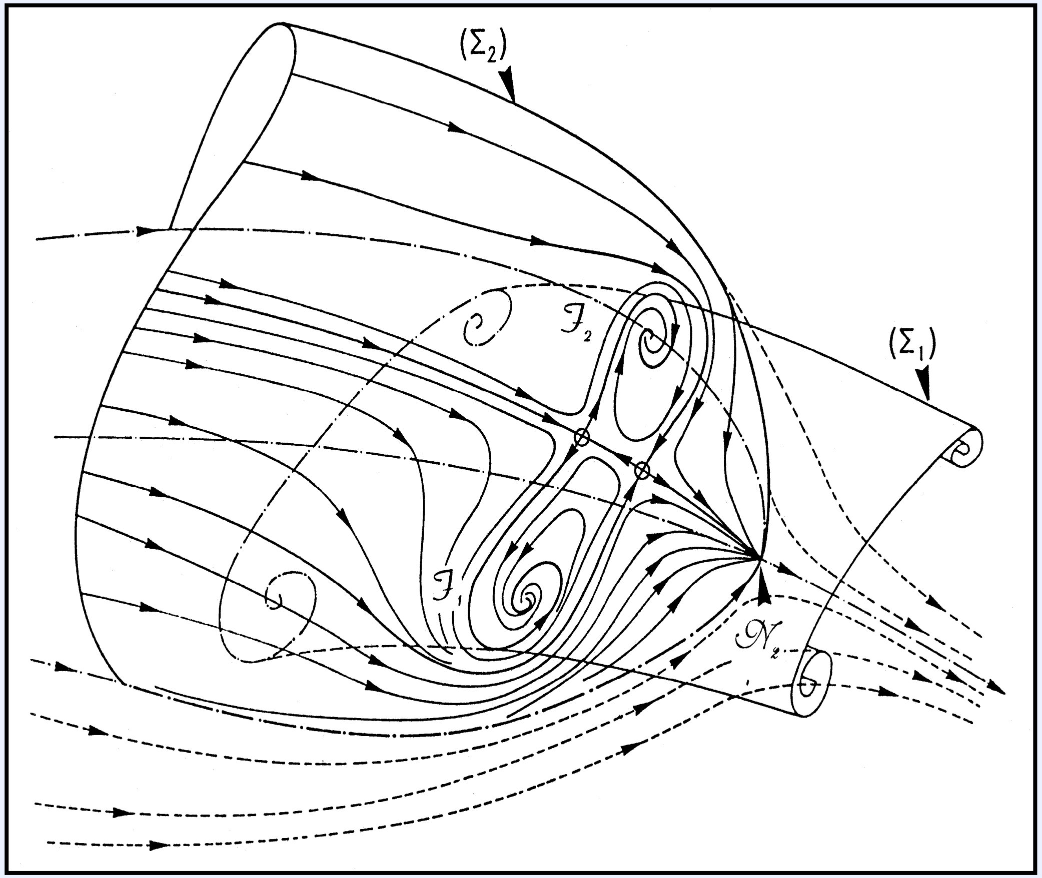


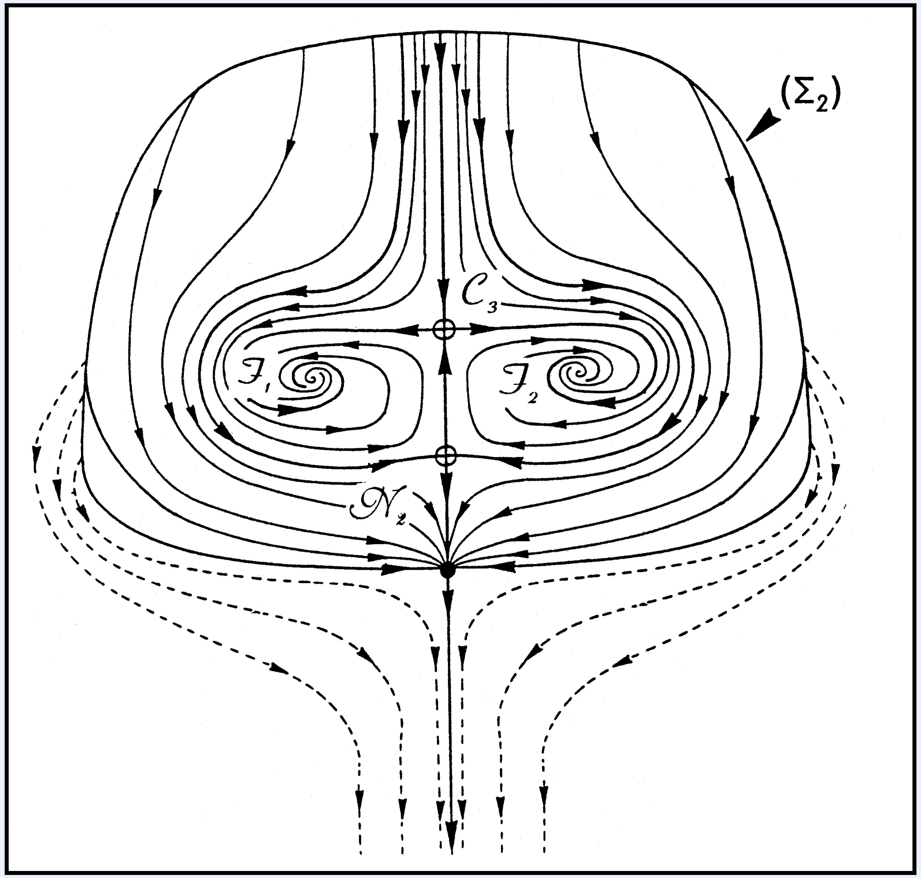
Crossing of the attachment surface by the tornado like vortices



Rolling up of the detachment surface

Detachment with two saddle points and two foci

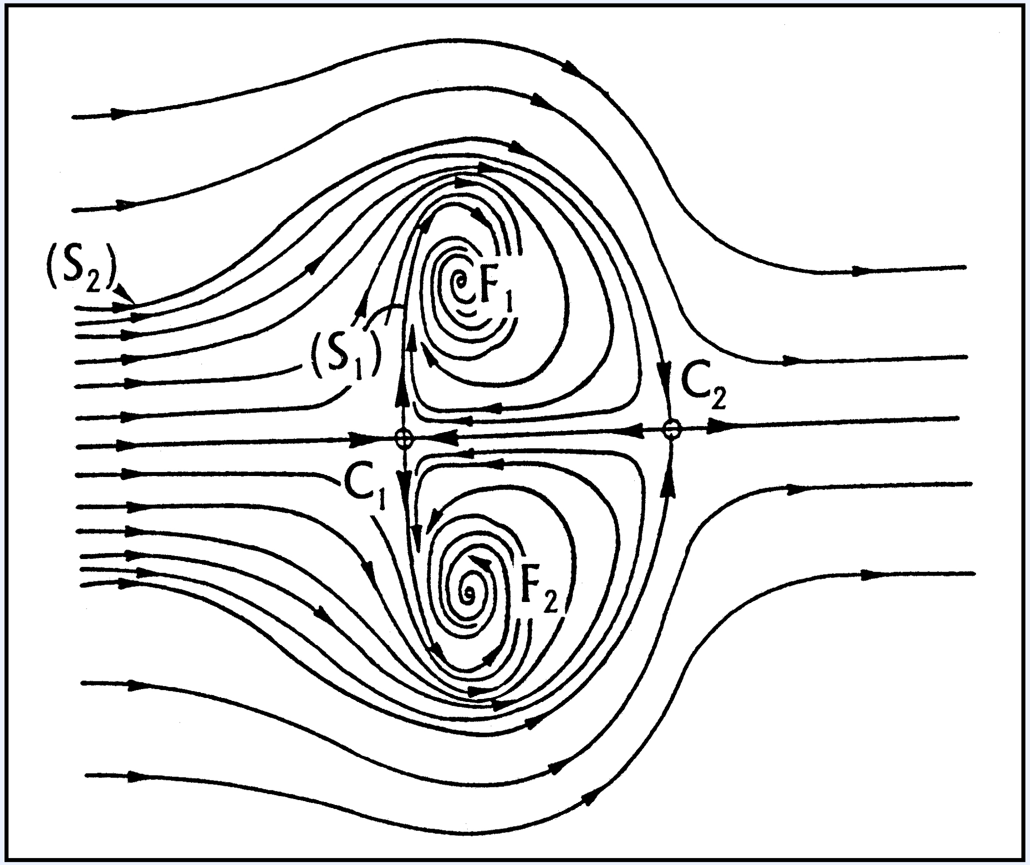


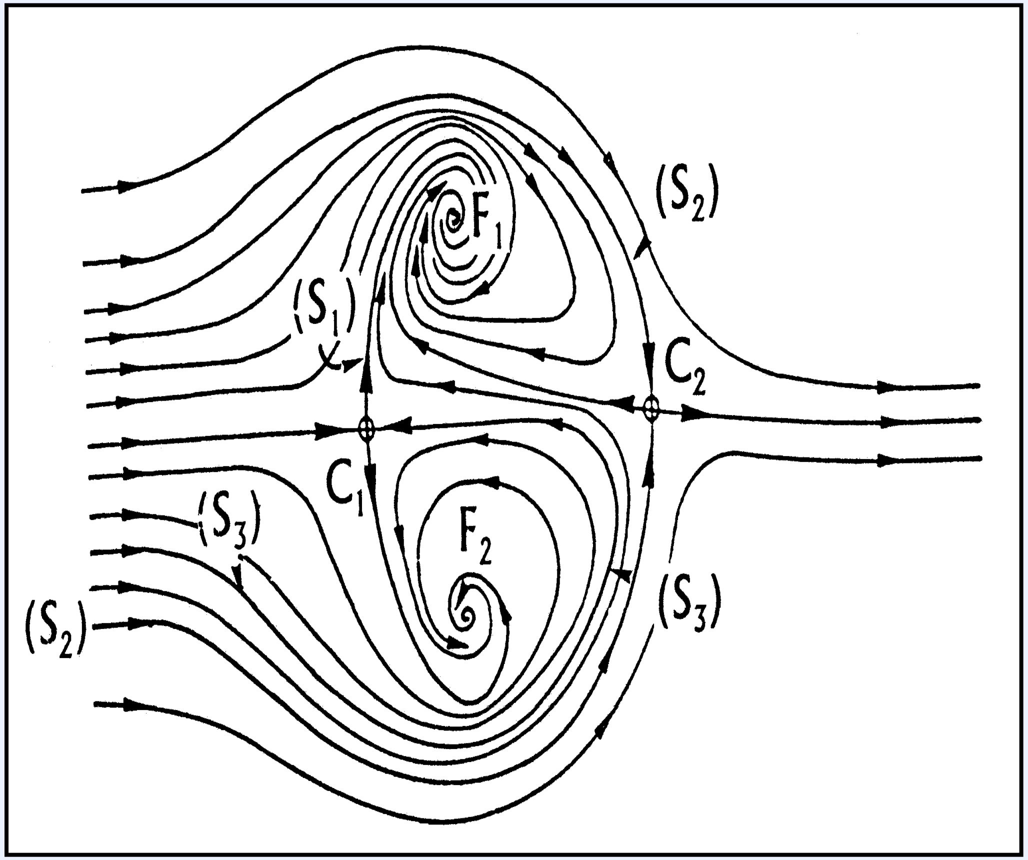


Flow on the attachment surface

Attachment surface seen from downstream

**Detachment with two saddle points and two foci.
Variants of the surface flow pattern**





Symmetrical topology (instable ?)

Real topology

Three-dimensional separation, definitions and results (1)

- A flow is separated (detached) if its skin friction line pattern contains more than two nodes.

Or equivalently :

- A flow is separated (detached) if its skin friction line pattern contains at least one saddle point.

Hence :

Every separated flow contain one or several saddle points

Three-dimensional separation, definitions and results (2)

- Through a saddle point go two separation lines (separatrices) which are either of the attachment or detachment type.

- A detachment (attachment) line is the trace on the obstacle of a detachment (attachment) surface.

- The streamlines forming an attachment surface terminate at a node coincident with the attachment saddle point on the obstacle surface.

- The streamlines forming a detachment surface emanate from a node coincident with the detachment saddle point on the obstacle surface.

Three-dimensional separation, definitions and results (3)

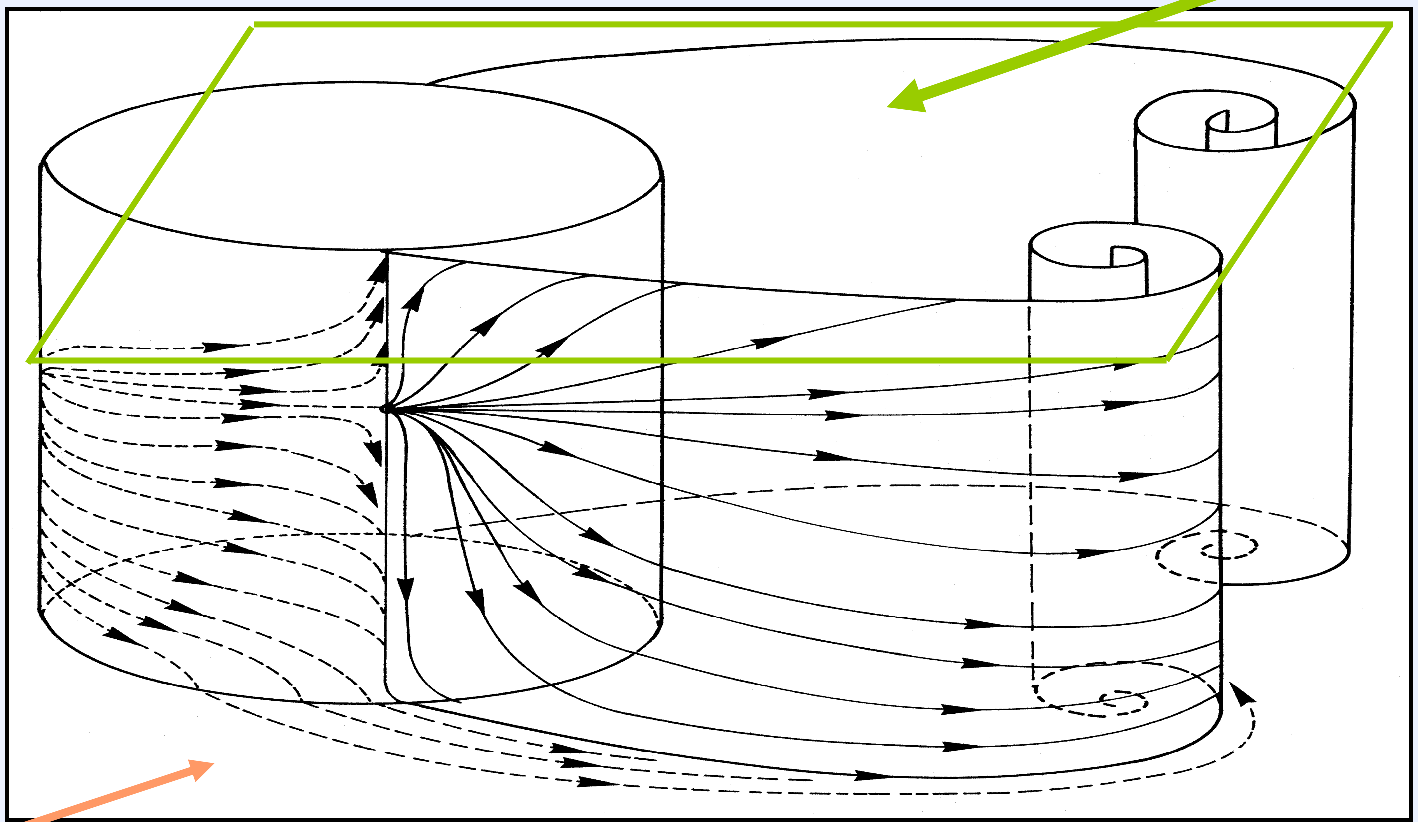
Helmholtz's theorem

- A vortex tube (vortical structure) cannot originate or end in a fluid.
- It must originate or end on a boundary (wall of free surface).
- Or form a closed structure or extend to infinity (in fact closing itself at large distance).

These theorems are true for inviscid flows: In fact, viscosity tends to dissipate the motion into heat so that the vortex extends to a finite distance (which is fortunate)

Three-dimensional separation, definitions and results (4)

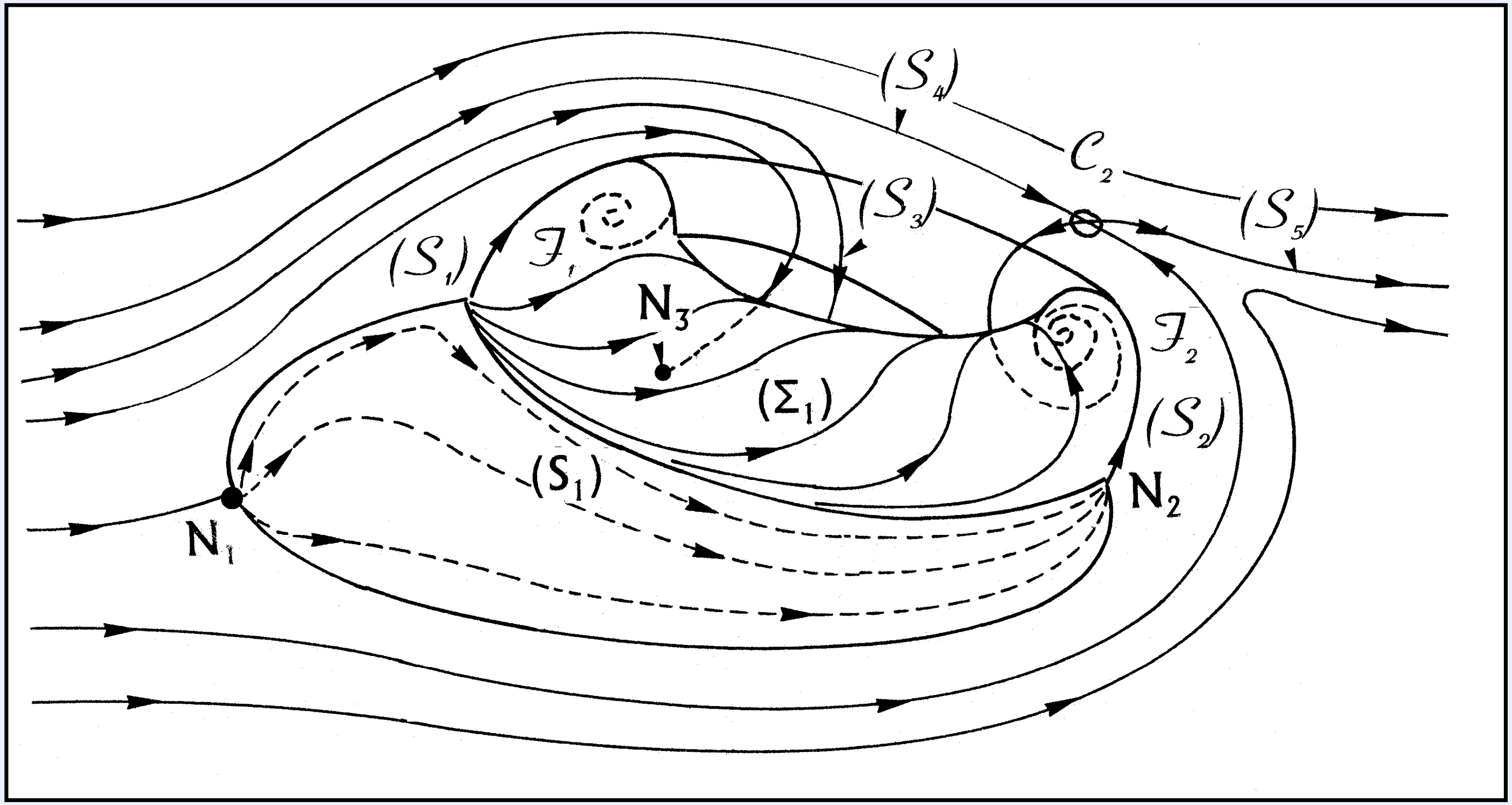
- It originates or ends on a wall or a free surface (interface water-air):



Tornado like vortices behind a bridge pier

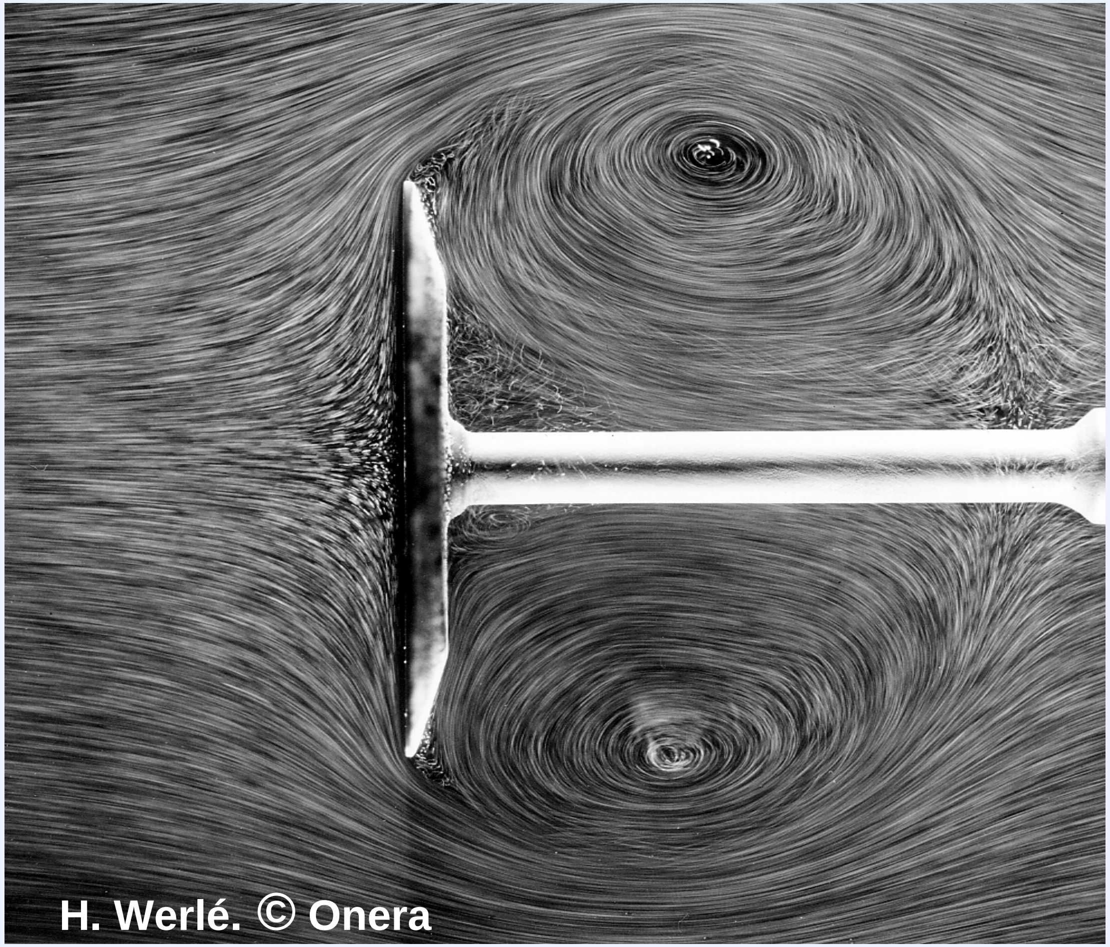
Three-dimensional separation, definitions and results (5)

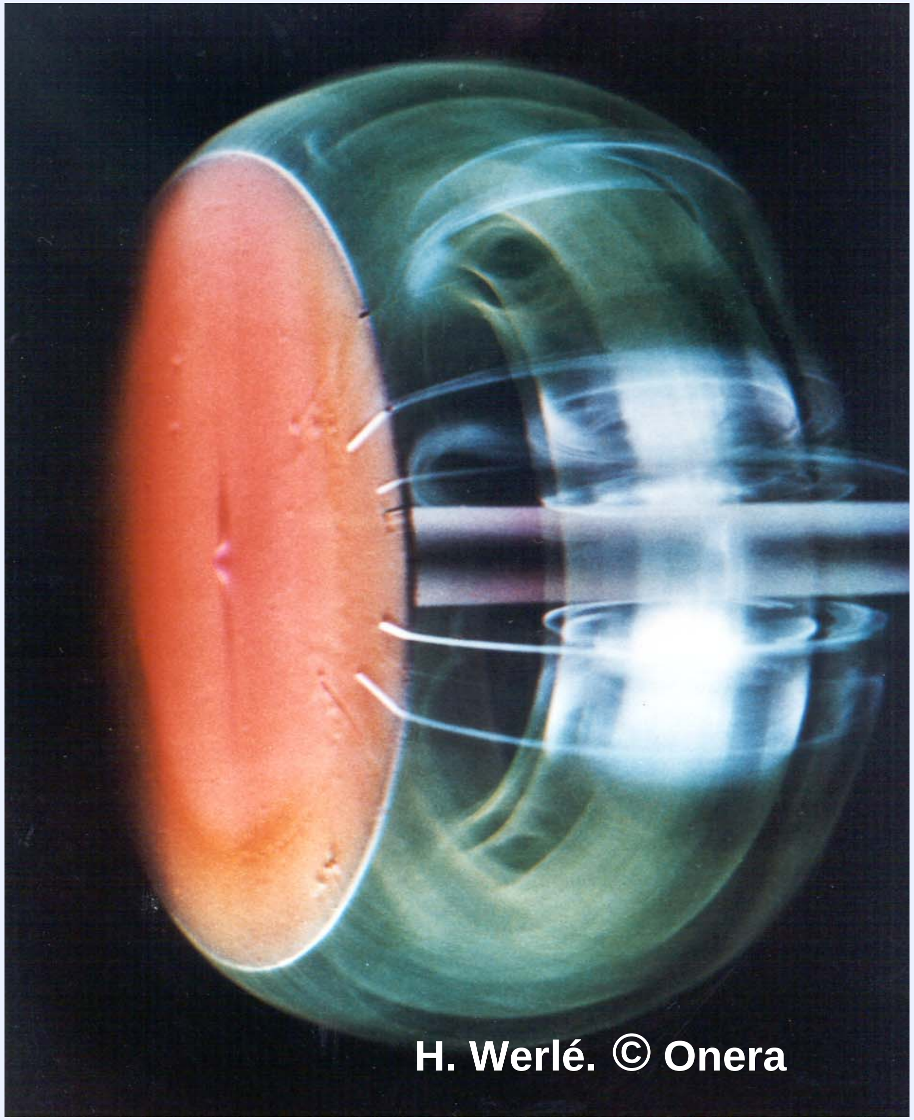
☆ Or forms a closed vortical structure



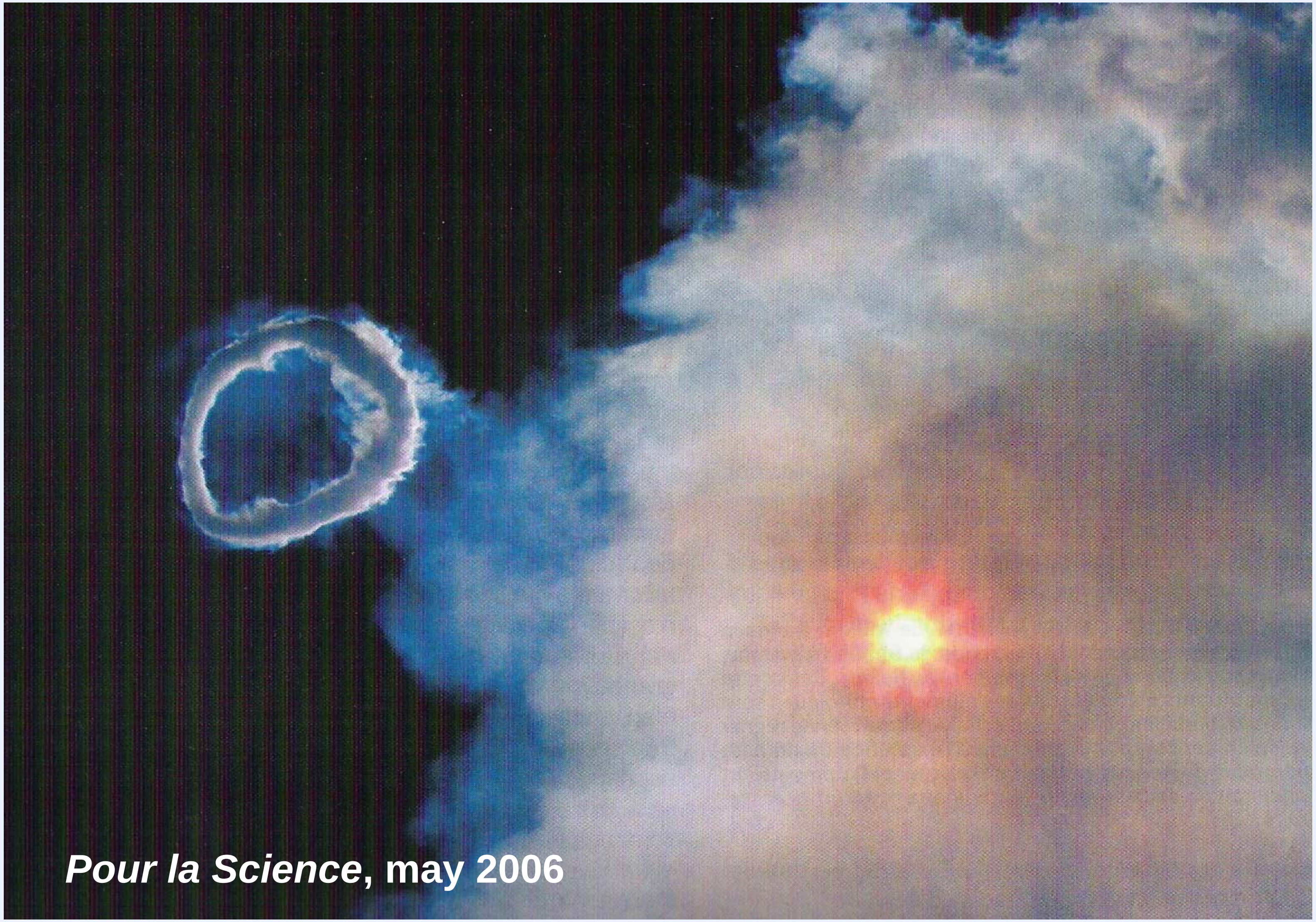
Toroidal (ring) vortex

Toroidal vortex behind a circular disk facing the flow





A big toroidal vortex: smoke ring emitted by volcano Etna



Three-dimensional separation, definitions and results (6)

➔ **The number of critical points on an isolated body must satisfy the Poincaré formula:**

$$\Sigma(\text{nodes} + \text{foci}) - \Sigma(\text{saddle points}) = 2 - 2p$$

➔ **Nodes and foci are topologically equivalent: they are sources or sinks for skin friction lines.**

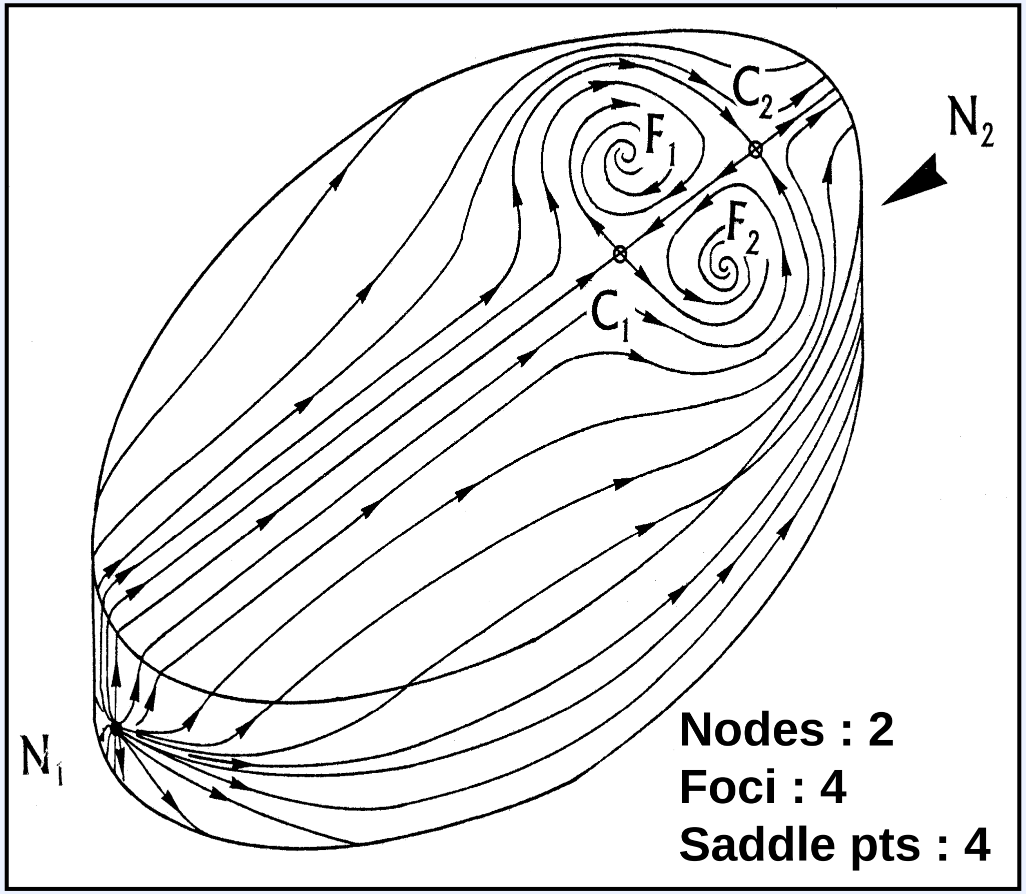
In the above formula p is the order of the surface:

- p = 0 – first kind (order 0): simple body like a sphere

- p = 1 – second kind (order 2): body with a hole like a torus

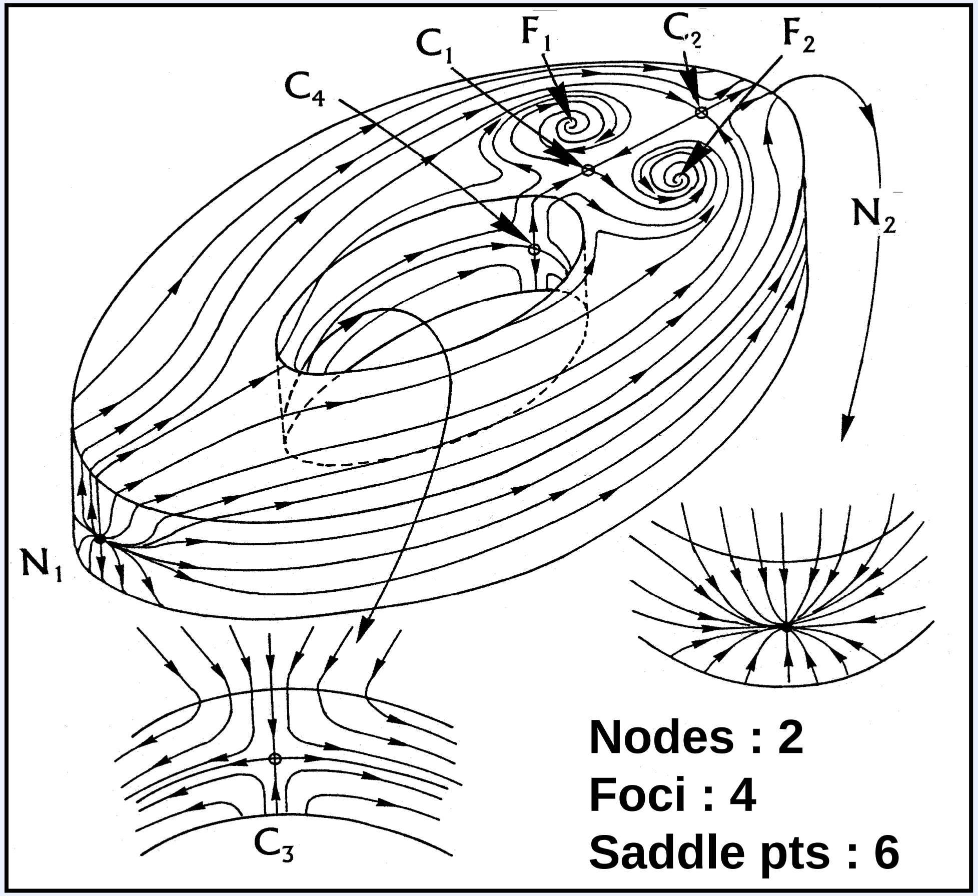
Three-dimensional separation. Order of a surface

Order zero surface



Σ (nodes+foci) - Σ (saddle pts) = 2

Order one surface



Σ (nodes+foci) - Σ (saddle pts) = 0

Three-dimensional separation

- ➔ In practice, the above formula is difficult to apply because a complete isolated body must be considered which is difficult for a wind tunnel experiment: one has to include the model + the support + the test section walls…

- ➔ However it can be useful to check the topological consistency of the reconstructed flow organisation.

Three-dimensional separation. Rules and precautions (1)

➔ Concepts deduced from the critical point theory can be applied to any vector field **sufficiently regular**; i.e., having a finite number of critical points.

➔ In particular, these concepts can be used to analyse the structure of the **velocity field projected in a plane**, which is commonly made to represent three-dimensional results.

➔ However, one has to be aware that in this case the representation of the field **is not objective** since it depends on the projection method.

Three-dimensional separation. Rules and precautions (2)

➔ Construction of a three-dimensional field from experimental or computation results **must follow a well defined procedure.**

➔ Firstly, one has to realise that the available information **is never fine enough** to allow a complete construction from the results: many details are blurred by experiment but also by the computation.

➔ Hence, several elements of the structure have to be imagined.

Three-dimensional separation. Rules and precautions (3)

The correct "strategy" is as follows:

1 - Inspect the skin friction line pattern to identify its critical points.

2 - Draw the separation lines, identifying detachment and attachment lines.

3 - Make sure that the surface pattern is topologically consistent: thus, any skin friction line must originate at a node and terminate either at a node or a focus. This operation may necessitate invention of critical points not visible on the visualisation.

Three-dimensional separation. Rules and precautions (4)

4 – After this first inspection, **define the outer flow structure** by making sure that it is consistent with the skin friction line pattern.

↓

5 – If this is not the case, modify the surface pattern and make a new attempt.

↓

6 – Define the structure of the **velocity field projected in well chosen planes.** Check the consistency of the projected field with the surface pattern.

↓

Three-dimensional separation. Rules and precautions (5)

7 – Do not forget some fundamental theorems: Kelvin, Helmholtz. **A vortex cannot originate nor terminate within a flow**, it must closes on itself or be in contact with a material boundary, or goes to infinity (except if destroyed by viscosity!)

8 – If one arrives at an « impossible » object, this means that some topological rule has been violated: then **try a new construction** by starting from step one and iterate!

Three-dimensional separation. Rules and precautions (6)

In complex flows, this exercise can become arduous, necessitating many trials before reaching a construction of the whole flow field which is topologically consistent.

This requires a good perception of three-dimensional objects.

Detachment vs. separation, reattachment vs. attachment

- The concept of separation implies the existence in the skin friction line pattern of at least one saddle point and associated separatrices or separation lines. It applies both to detachment and to reattachment.

- *Separation* is commonly used in English to designate detachment. The two terms are considered as equivalent but this leads to an ambiguity.

- The denomination reattachment implies existence of a previous detachment: the detached flow reattaches on the surface.

- In general, a behaviour of the attachment type is not associated to a previous detachment. Furthermore, in three-dimensions the fluid that reattaches is distinct from the fluid that detached from the wall.

- Except in special cases, the term attachment should be preferred to reattachment.